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TRANSACTIONS *of the* ILLUMINATING ENGINEERING SOCIETY

Founded in London in 1909 and incorporated in 1930

Volume 26 Number 3 — 1961

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The opinions expressed by authors and contributors to discussions are those of the individuals concerned and are not necessarily those of the Society

Presentation of Honorary Fellowship Certificate to H.R.H. The Duke of Edinburgh

At the Sessional Meeting held in London on Tuesday, April 11, 1961, at the Institution of Electrical Engineers, the Society was honoured by the presence of H.R.H. The Duke of Edinburgh, K.G., K.T., who received from the President a certificate recording his election as the first Honorary Fellow of the Society.

In opening the meeting the President, Dr W. S. Stiles, O.B.E., F.R.S., recalled that in 1959, the Golden Jubilee year of the Society, His Royal Highness showed his interest in the work of the Society by graciously consenting to become the Society's first Honorary Fellow. This evening he further distinguished the Society by attending a Sessional Meeting to accept a Certificate of Honorary Fellowship and to hear the discourse to follow.

The President recalled the purpose for which the Society was founded in 1909 and said that in the succeeding fifty years, with the remarkable technical progress in lighting and the growth of the lighting industry, the Society had fulfilled its role as a unifying body and is today recognised as the authority in this country on all lighting matters. He briefly reviewed the main lines of research and development in lighting that the Society aims to foster. Successive papers in the Transactions recorded the mounting efficiency with which power could be converted into light; new processes of light production gave greater flexibility and presented new opportunities but they also created new problems. The Society was also concerned with the means of redistributing light from the source so that it could be used most effectively. New light sources and new materials had proved powerful factors in the integration of lighting with interior architecture and the lighting engineer was aware that real progress in lighting applications will be made only if he advances hand-in-hand with those concerned as much with the aesthetic as with the utilitarian aspects of lighting environment. The Society also had a deep interest in all that concerned the capabilities and limitations of human vision with particular reference to the provision of lighting adequate to the task in hand and free of deleterious effects on vision.

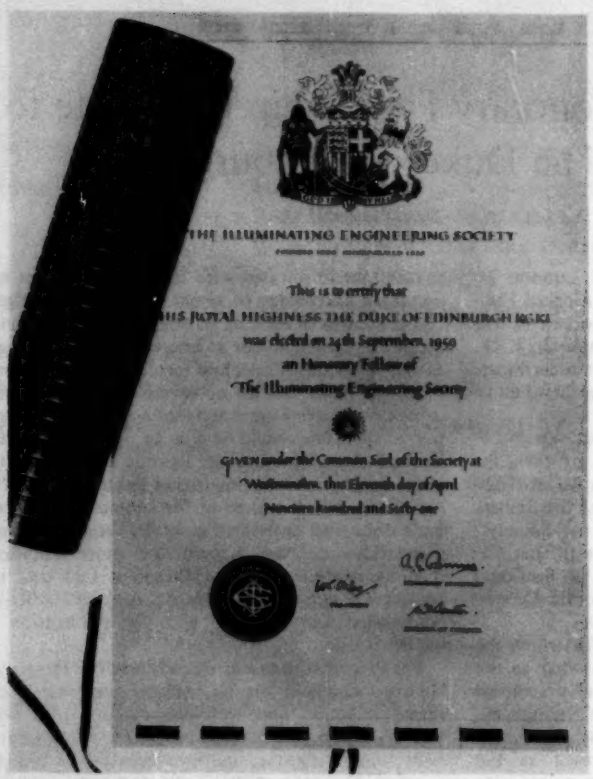
Another important function of the Society was to ensure that in parallel with technical advances and increased knowledge of visual requirement the general standards of lighting throughout the community should be raised. As far as interior lighting was concerned, the I.E.S. Code, first introduced in 1936, provided the main tool for achieving this object. It became evident a few years ago that a major reconstruction of the Code would have to be undertaken in the light of changing ideas on lighting design and the practicability of achieving higher lighting levels. The new Code, which was to be the subject of the evening's discourse, embodied carefully weighed recommendations and was a great deal more ambitious than its predecessors. The President said that the Society was delighted that the occasion of His Royal Highness's visit coincided with the publication of the new Code.

The President then addressed himself to His Royal Highness and said 'Sir, we are conscious that in the varied scientific and technological activities with which you are associated, your interest is always a most penetrating one, and in consenting to become our first Honorary Fellow you not only confer a great distinction on the Society but you put the Society on its mettle to pursue with added vigour the important objects for which it stands. I have the great privilege on behalf of The Illuminating Engineering Society to declare you its Honorary Fellow and to hand you this certificate.'

In acknowledging the presentation His Royal Highness said—'Thank you very much indeed for this very delightful certificate. I hope you will be able to keep up the standard with your other Honorary Fellows in due course. May I also take this opportunity to offer my rather belated good wishes on your Jubilee which I missed, I regret to say.

'It gives me very great pleasure to join you this evening, or rather now that I have been an Honorary Fellow of the Society for some time.

'I have a peculiar interest in lighting as unlike a good many of you the houses I live in were all designed before electric lighting was invented and one of the interesting problems, which I don't think is covered by the new Code, is how to install electric lighting in houses which were intended for an en-


THE ILLUMINATING ENGINEERING SOCIETY

This is to certify that

HIS ROYAL HIGHNESS THE DUKE OF EDINBURGH K.G. K.T.

was elected on 24th September, 1959

an Honorary Fellow of

The Illuminating Engineering Society

GIVEN under the Common Seal of the Society at

Westminster, this Eleventh day of April

Nineteen hundred and Sixty-one

The Certificate of Honorary Fellowship and case presented to H.R.H. The Duke of Edinburgh

The President, Dr. W. S. Stiles, presenting the Certificate to His Royal Highness

tirely different kind of lighting. As you can imagine any given number of people will have the same number of opinions on the subject.

'We are going through a particularly fascinating time in this business of lighting. The old days were rather restricted in the number of light sources which were available to light whatever you wanted to light; we were stuck with candles and had to make the best use of them. Today there are altogether too many and the problem is to choose the right one and I think that, if I may say so, we are all, or you are all, groping for the right answer. I don't think we have found it yet, but I am sure that by using all available means and by a process of elimination we shall eventually achieve a reasonable standard of lighting for different purposes.

'Quite apart from the number of different sources of light there are the technical problems of lighting things with the right colour, direction and intensity, and making it acceptable to human taste—not an easy job, and I sympathise with you. There are other interesting sides; for instance I drive a motor-car and I think we have a long way to go in the way in which motor-cars light up the way ahead and the way in which local authorities light, or attempt to light, the road. As you know, I also sometimes fly an aircraft; again we have only got half-way to the answer of lighting runways at night or for lighting up airfields so that aircraft can get about readily without reference to instruments, except in fog where instruments are necessary.'

The New Code

Immediately after the presentation to H.R.H. The Duke of Edinburgh the President introduced Dr W. E. Harper who, he explained, had been responsible for co-ordinating the work of a number of study panels of the I.E.S. Technical Committee and for drafting the new Code, and called upon him to present his lecture.

Dr Harper began by explaining that he proposed to deal with the ideas which shaped the thinking of the members of the Drafting Committee responsible for the preparation of the Code.

The Committee's first step was to agree the approach, and it was accepted from the outset that the Committee's concern was with the design of the whole visual field, that is, with the total pattern of light, shade and colour created within a room or building. It was recognised that the appearance of an interior not only exerts a profound effect on the outlook and response of the occupants but also on the ease with which important detail is seen and the degree of visual fatigue experienced.

The task of prescribing the visual fields suited to different situations was approached by isolating its most important features and treating each separately although it was realised that in practice these components are never separated in this way but are parts of the whole field which is perceived in its entirety. The first component to be so treated was the pattern of brightness, and as the pattern is usually complex it was found necessary to break the pattern down into four major areas: the work itself, the background against which the work is seen, the general surroundings, and the light sources.

In most cases, the work being done is the focus of interest and this gave a natural starting point for designing the brightness pattern of the complete interior. The first step was to make sure that the work is made bright enough for all the essential detail to be seen easily and quickly. There were two considerations here: first, the nature of the task and second, the visual efficiency (speed and accuracy) with which the detail is seen. It was not necessarily a simple question of aiming for maximum possible visual efficiency at all times, since highly exacting tasks would then require very high levels of brightness which might not always be justified by the resultant benefits. In many cases, users' needs will be met by a more realistic standard of visual performance.

The Committee, then, was faced with a choice of two criteria for visual efficiency: either 'maximum possible' (which the Americans have adopted following Blackwell's work) or 'near maximum', which was the criterion developed by Weston in this country and which formed the basis of the 1955 Code. It was decided, in the context of conditions prevailing in this country, to continue to base the illumination recommendations on Weston's criterion, this having a notable advantage of permitting adjustments to be made in standards from time to time.

The recommendations, however, were not made solely on grounds of visual efficiency. It was felt that modern ideas on amenity call for a certain minimum illumination; most people today expect a well-lighted building even though their work may call only for casual vision.

Having established the basis for determining task brightness, it was then necessary to relate the task brightness to the brightnesses of the task background and general surroundings. Of the task background, it was desired to arrange the brightness pattern so that attention would be drawn naturally to the work without creating a risk of visual discomfort or strain, by undue contast between the task and its background. The Committee therefore recommended that, broadly, the background brightness should be approximately one-third of the task brightness. In an office, for example, this would mean replacing dark polished wood desks for something much lighter.

In making recommendations for the brightness of

the general surroundings, however, the Committee was faced with a much greater difficulty in view of the lack of relevant data, and was thus able only to give quantitative guidance for the average brightness. In suggesting an average brightness of about one-tenth of that of the task, the Committee did not want this to be interpreted too literally; average brightness was not to be confused with uniform brightness which was the last thing the Committee wanted to suggest. It was also important here to remember that the desired result would be obtained only when the lighting was designed in conjunction with the choice of finishes for the various room surfaces, which required close collaboration between architect and lighting engineer.

One important consequence of the illumination recommendations was their impact on fenestration. In those cases where the room and window dimensions prevent the recommended illumination from being achieved without excessive sky glare, the Committee felt that the building designer should feel free to reconsider the design of his windows to give full weight to such other factors as heat loss and appearance and then achieve the functional lighting requirements by supplementing the natural lighting with properly designed artificial lighting intended to operate permanently during the daytime. This means more than putting in sufficient artificial lighting to 'top up' the day-lighting; it means designing the artificial lighting to give a good balance of brightness which also leaves the occupant with the impression that the interior is being lighted by daylight. How this could be done was ingeniously demonstrated by a double projection technique.

Having shown how the Committee established limits controlling the brightness pattern in an interior, Dr Harper reminded his audience that the brightness pattern, although fundamental to a lighting scheme, was but one component of the visual field and he went on to show how they dealt with some of the other components. The first of these was the effect known as modelling, in which directional lighting is used to give shape and solidity to objects. The Committee wanted to show that, used in a general way, directional lighting can reveal the architectural form of buildings and can improve the appearance of people and objects within them. In a more specific way, it can be invaluable in revealing additional detail in the task. The Committee feit that this work was now so well established that some guidance on it could be included.

Another component felt to be of sufficient importance to warrant inclusion was colour rendering. The Committee distinguished two categories; in a general way, it felt there were so many occupations where pleasant colour rendering is important to welfare and amenity that it should be given as much consideration as luminous efficiency in the choice of light source. It also emphasised the need for accurate colour rendering for those situations which involve colour matching or appreciation.

Dr Harper left to the last the recommendations made for controlling glare. Even if all the other factors have been correctly designed, an installation may still be ineffective by having excessive glare. The Committee felt that the work carried out at the Building Research Station justified a new appoach to the problem, based on the BRS glare formula but modified to obtain more convenient numerical values by converting the glare constant into a glare index.

From this starting point, the Committee was faced with two problems. It had first to decide the degree of glare which could be accepted without discomfort in different situations and express that degree numerically as limiting values of glare index. Then it had to devise a method by which the practising engineer could calculate quickly and easily the glare index for the particular installation he was designing and compare it with the recommended limit.

It was agreed that the amount of tolerable glare depended on the nature of the task and that what was needed was a series of limiting values of glare index which would express this difference. To determine the series, a team of observers made subjective assessments of glare at about 100 installations, combined their observations with laboratory and field data and then translated the results into the limiting values given in the Code. These values refer to the glare experienced by the occupants of a building when they look up from their work. Having determined the permissible degree of glare for particular situations, the Committee then tackled the problem of glare calculation for a proposed installation, and with the aid of an electronic computer, were able to prepare tables from which the glare index for a general lighting installation under a wide range of conditions could be derived in a matter of minutes. The tables are limited to artificial lighting installations, in which the fittings are arranged regularly overhead but even then they cover many situations encountered in normal practice.

Dr Harper illustrated his lecture with demonstrations and coloured slides and concluded with a film on the I.E.S. Glare Index System.

The meeting was attended by 600 members and invited guests. Before the meeting began the officers of the Society had the honour of being presented to H.R.H. The Duke of Edinburgh.

UDC 628.93

Modern Aids to Lighting Design—Computer Techniques

By H. E. BELLCHAMBERS, A.M.I.E.E. (*Fellow*), G. K. LAMBERT, B.Sc. (Eng.), A.M.I.Mech.E., A.M.I.E.E. (*Fellow*) and H. R. RUFF, B.Sc. (Eng.), M.I.E.E. (*Fellow*)

Summary

Modern lamp designs and improved lighting techniques need for their full development a tremendous number of calculations. Electronic computers make these practicable by overcoming their tedium and cost. The basis of analogue and digital computers is explained. Analogue computers are shown to be particularly useful for elucidating interior lighting design problems. The prodigious speed of digital computers rapidly completes complex calculations necessary for examining lamp and equipment designs, and lighting installations. The application to flux distributions, interreflections, luminance patterns and glare in interiors, and to streetlighting performance and floodlighting illumination in exterior lighting is followed in some detail. Tabulated data from research investigations will enable the lighting engineer to improve his design fairly simply, and some routine problems are already being referred to the computer as a matter of course.

(1) Introduction

Modestly, lighting engineers may think their calculations do not justify the use of an electronic computer, comparing its use with that of a steam hammer to crack a nut. In fact, advanced lighting calculations are often eminently suitable for digital computer programming techniques, in that relatively simple calculation routines need to be repeated for a large number of points, and the computer is the most economic way for performing these calculations. Examples are the evaluation of form factors, interreflections, glare ratings and direct ratios required for coefficient of utilization calculations. Analogue computers can assist in solving design problems in interiors where luminance distributions are non-uniform, and have the advantage that the effects of changes in surface reflectivities or light distribution can be observed as changes are made.

This paper has been arranged to describe some of the uses to which computers have been put in the service of lighting, to explain the way in which the lighting engineer should transform his data so that they are convenient for computer programmes, and to show some of the results of this work.

The lighting engineer need not concern himself with the detailed programming of the computer, still less with the electronics of its operation; both are naturally better accomplished by a specialist conversant with the particular computer and fully up-to-date with its programming techniques. However, he will need to put his problem into a form suitable for calculation and to indicate clearly the data that will be supplied, together with the form and magnitude of the results and mathematical steps by which they can be derived, although these may be modified in discussion with the programmer, as sometimes one method of calculation or data presentation may be advantageous. The programmer will then be responsible for the preparation of the programme; as the occasion arises the lighting engineer will send along a set of data, in the agreed form, to the computer office, and the computer will process the data and print the results.

The authors are with the AEI Lamp and Lighting Co, Ltd. The manuscript for this paper was first received on August 2, 1960 and in revised form on October 21, 1960. The paper was presented at a meeting of the Society in London on January 9, 1961.

(2) Types of Computing Equipment

(2.1) The analogue computer

The layman's conception of an analogue computer is what would nowadays be called a direct analogue, for instance a network built for determination of fault currents in a particular power distribution network. Recent analogue computers comprise electrical components, each performing a specific function (such as the operation of integration) and needing to be cross-connected to suit a particular problem. It deals with quantities not numbers, and its operations may be likened to graphical methods as distinct from numerical ones. The number of units in the analogue limits the number of operations, but this disadvantage is offset by the shortness of the operating time—a matter of a few seconds only—which makes it possible to observe transient effects and to watch the result of variation of problem parameters. In this way it is easy to determine the value of a parameter needed to produce a required result.

Fig. 1. Direct analogue for determining interreflections in rectangular rooms (left) with (right) scale model variable room on which illumination measurements can be made.

For lighting calculations the large versatile analogue computer is less suitable than the simple direct analogue network, the scope of which is well illustrated by the outstanding work of O'Brien. An example of the direct analogue is a very simple network to simulate the luminous flux exchanges which take place in a lighted interior. Fig. 1 shows a direct analogue computer and a model room by which the results obtained by theoretical and practical approaches to interreflection problems can be compared.

(2.2) The digital computer

The digital computer is the type most generally useful for solving lighting problems. This is a machine equipped to carry out numerical operations with figures (i.e. digits), and is 'set-up' for a particular job by feeding into it ('reading in') a programme, i.e. a detailed series of instructions on how it is to handle the data which will follow.

(2.2.1) *Component units and operation*

There are considerable differences in the speed and capacity of different types of digital computer, but they comprise generally the units indicated in Fig. 2, and their basic methods of operation are the same.

Computer arithmetic consists in breaking a calculation down into its elemental steps. The data are brought in to the arithmetic unit, as required, for

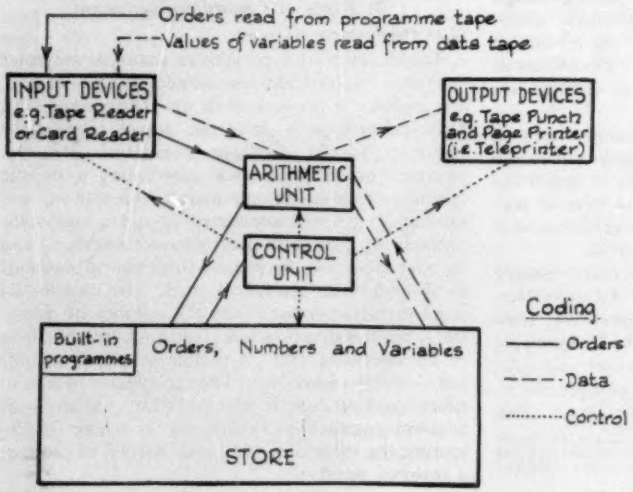


Fig. 2. Schematic diagram of digital computer showing functions and interelation of its components.

these elemental operations to be performed, and then returned to the store until required for what the draughtsman would call sub-assemblies; these in turn are stored until required for the final assembly, which in turn may be stored until a whole series of such totals are calculated and then printed out.

The 'Input Devices' are the means by which information is fed to the computer. The medium may be paper tape punched in a variant of the ordinary teleprinter code, punched cards, or magnetic wire or tape as used on a tape recorder. In each case the input device converts the information into a series of electrical pulses similar to that of a morse code or teleprinter transmission. The Creed tape reader uses small filament lamps and photocells to scan the tape; only where a hole is punched a pulse results. The tape is rapidly stepped along, like a cine film, as required by the 'Control Unit'.

The control unit is itself directed by means of programmes placed in the permanent store of the computer by its manufacturers and called in by indication signs on the programme tape. The electric pulses from one symbol on the tape go into the 'Arithmetic Unit' where they are identified by the control unit. Invariably the whole of the programme of orders is read into the computer store before the data for the particular calculation are read in and before the calculation is started. Occasionally symbols act as an indication to the control unit concerning the reading of the programme, but generally they are converted to binary code and stored. A working knowledge of the binary code helps the computer programmer while he is developing and testing his programme, but the lighting engineer need not be concerned about the conversion, which is fully automatic. Operations in the arithmetic unit may well be visualized in terms of the operation of desk calculators.

The built-in programme acting through the control unit causes the binary coded orders and numbers to be transferred to location or pigeon holes in the 'Store' in an orderly fashion. A common form of store is the magnetic drum—a rapidly revolving cylinder the surface of which is coated with magnetic oxide. Pairs of coils are mounted close to the surface of the drum; one of each pair is the writing head which translates the series of electric pulses into a series of magnetized spots spaced round the surface of the drum, and these can be read by the second coil or reading head as they pass without being obliterated. In one computer employing a drum store, a single 'word' has room for 39 pulses (or binary digits) each lasting for 3 microseconds; a 3 digit space is arranged between words. The drum has a speed of 3,720 rpm, and each of its forty tracks can accommodate 128 words. The storage accommodation is large, but the average access time is long, 0·323 milliseconds. It achieves fast operation by automatically transferring blocks of data or orders from the drum store into a smaller quick-access store of nickel delay lines. Each line accommodates one 'word', and the access time is only 0·066 milliseconds.

After causing the series of orders comprising the programme to be taken into the arithmetic unit, digested and stored, the control unit encounters the indication to act on the orders. The programmer will have made the first order something like 'Stand by for data and read them when you get the signal.' While the programme tape is being read, the operator will have threaded the data tape into a second tape reader and will restart the computer. Usually the whole set of data will be read in before calculation commences, but occasionally the data will be read in steps, as in the floodlighting calculations described later.

On completion of the calculation the control unit will deliver the results to the 'Output Device' via the arithmetic unit, where it is converted to decimal notation. From the computer's built-in programme the control unit intersperses the result figures with instructions on printing out (line shift, carriage feed, space etc.) so that the figures are printed in any chosen format. The output device may be a teleprinter or a Creed tape punch, which can punch results on paper tape at twice the speed that a teleprinter can print them, the tape later being transcribed by the teleprinter. The latest developments include line-at-a-time printing equipment; in this the paper is struck against type on a rapidly rotating band at the instant the required character is passing.

(2.2.2) *The computer room*

There is usually a bias in design of computers towards suitability for processing commercial data, (when store size may be a primary consideration) or for scientific and engineering calculations (when flexibility and ease of programming are main considerations). Medium-sized computers of the latter type are the most suitable generally for lighting calculations. The Pegasus computer is of this type, and is the one chosen for illustration.

A typical computer room layout, with punched tape input and output, is shown in Fig. 3. In the centre is the computer with its control desk; below are the control panel and monitoring oscilloscopes. The tape readers are to the left of the operator and the output punch and page printer to the right. The separate power supply cabinet, with voltage stabilization, is to the rear. Around the walls are ancillary equipment—tape winders, punches etc. Programme

Fig. 3. The 'Pegasus' computer room at Rugby.

and data tapes are usually punched on equipment in a separate room; programming and administration are in separate offices, and a workshop off the computer room is provided for the maintenance engineer.

The computer is constructed in three sections. The foremost contains the main store in the form of a magnetic drum and associated equipment; the middle and rear sections contain mainly 'plug-in' electronic units in which the arithmetic and logical operations are carried out.

Appendix 1 shows how a simple lighting calculation is handled by this computer, including programming in a simplified computer code.

Basic principles for programming for a digital computer are:

(1) the computation should be reduced to a pattern which needs programming but once, to exploit the advantage of the computer in being able to run through this pattern for a large number of points;
(2) the programme should be as flexible and as universal as possible, able to cope with the whole range of types of equipment and data for the particular type of calculation, any steps not required on a particular occasion being 'jumped';
(3) the programme should be built up in an orderly way so that modifications needed later can be fitted in.

These principles have led to the remarkable similarity between the AEI programme described below for calculation of area floodlighting illumination on Pegasus, and the one described by Gough for the IBM 704 computer.[1]

(3) Examples of Computer Techniques in Research

Already these new tools have been grasped by the research and development engineers to make more complete studies of complex lighting problems. Examples which will be examined in detail are calculations of flux distribution and glare rating for interiors, and a study of street lighting performance in terms of road illumination, road brightness, revealing power and glare, as a driver travels along an installation.

(3.1) Interreflections

The luminance distribution in a room due to the direct illumination of its surfaces by the light sources and that added by interreflections between the surfaces is complex. Studies directed towards a better understanding began by introducing certain simplifications—for example room surfaces of uniform reflectance, uniformly illuminated and uniformly diffusing—enabling relationships to be expressed in mathematical terms. Errors are reduced if the light-emitting surfaces are broken down into small elements, but this leads to repeated operations which are time-consuming. The use of computers for these calculations makes possible this more exact approach to interreflection problems, and furthermore, allowance can be made for asymmetrical arrangements of light sources and variations in surface reflectivities.

The distribution of radiant flux within a room is generally expressed in the following form:

$$L_1 = L_{o1} + \rho_1 E_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where L_1 is the total luminous emittance of finite

surface A_1 including all interreflections, L_{o1} the initial luminance of surface A_1 (excluding interreflections), ρ_1 the reflectance of surface A_1, E_1 the total illumination of surface A_1 by all the surfaces in the room which 'see' A_1, including interreflections.

Equation (1) may be written:

$$L_1 = L_{o1} + \rho_1 (L_2 f_{12} + L_3 f_{13} + \ldots . L_n f_{1n}) \ldots\ldots \quad (2)$$

where L_2, $L_3 \ldots . L_n$ are the total luminous emittances of those areas A_2, A_3, $\ldots . A_n$ which are visible from A_1, and f_{1n}, form factor of area A_1 with respect to area A_n, is the fraction of diffuse flux leaving area A_1 that is received directly by area A_n.

$$f_{1n} = \frac{1}{\pi A_1} \int_{A_1} \int_{A_n} \frac{\cos \theta_1 \cos \theta_n}{r^2} \, dA_n \, dA_1$$

where θ_1 and θ_n are the angles between the normals to surface elements dA_1 and dA_n, and the line joining these elements, r is the length of the line joining the surface elements dA_1 and dA_n. O'Brien[2] has shown that equation (2) can be rearranged in a form which defines an equivalent circuit or network, and this can be used to simulate the flux transfer within a room with any distribution of primary sources and surface reflectances. The potentials of the network represent the luminous emittances; the surface reflectances and form factors are related to the circuit impedances.

Fig. 4 shows the network representing a rectangular room in which the luminous input is symmetrical and surface reflectivities are uniform for each surface. When current is set proportional to the luminous input, the potentials measured at L_1, L_2 and L_3 are proportional to the average total luminous emittances of the three surfaces A_1, A_2, A_3.

The circuit and components for an analogue computer for interior luminance design are shown in Fig. 5. Flux input is set as a potential at the input nodes, and for surfaces where there is no input the input node is connected to earth potential. A variable resistance related to surface reflectance is

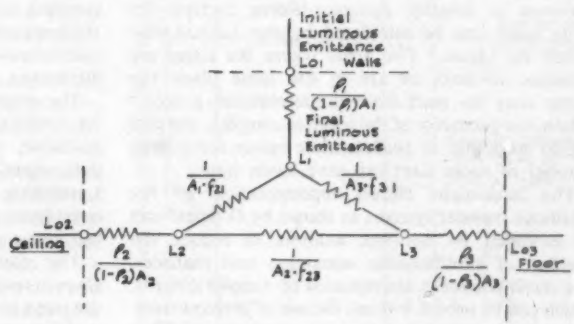


Fig. 4. Network of resistances representing interreflection conditions in a rectangular room: L_{o1}, L_{o2}, L_{o3} are the values of luminance due to light flux originating in walls, ceiling and floor respectively and L_1, L_2, L_3 are those due to total flux emitted including interreflected light.

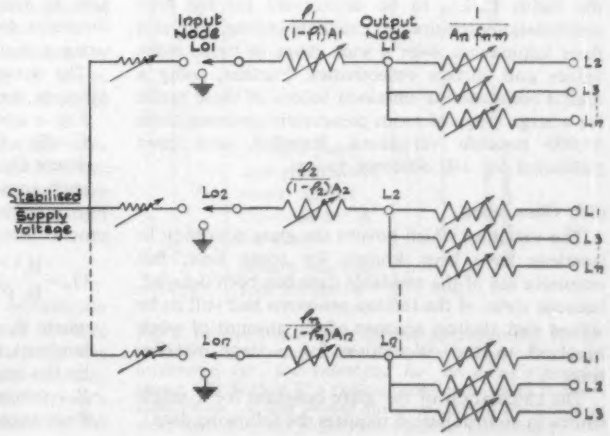


Fig. 5. Circuit of a practical direct analogue network for determining the luminance distribution in a rectangular room. The equipment is shown in Fig. 1.

connected between each input node L_{on} and the total luminous emittance nodes L_n; for black surfaces the value of this resistance is zero and for perfectly white surfaces infinite. The variable resistances representing form factors for the various areas are connected between the appropriate luminous emittance nodes L_n. Values of total luminous emittance are then obtained by measuring the potentials of each of the total emittance nodes L_n to earth.

Problems in a variety of forms can be solved using such an analogue. Generally the geometry of the room, surface reflectances and flux inputs are known, and the problem is to determine the final total luminance of the room surfaces. On the other hand the final surface luminance may have been specified, and surface reflectances can then be determined to provide the desired final luminance.

For each problem the form factors relating to the geometry of the room must be determined, and, where the luminous emittances required are for areas which are part of a surface, the calculation becomes a lengthy process. Form factors for finite areas can be calculated by the method described by Moon.[3] For areas where the edges are common to both or are in the same plane the factor may be read from predetermined graphs.[4] Where the geometry of the room is complex, use of a digital computer to predetermine values for a large number of room sizes can save much time.

The equivalent circuit representation of the luminous transfer systems as shown by O'Brien[5] can be modified by network analysis to reduce the number of simultaneous equations and matrices. The mesh networks are replaced by simpler circuits, which can be solved without the use of determinants. Using this method he obtained equations enabling the ratios L_n/L_{on} to be determined for the nine combinations required to calculate ceiling, wall and floor luminances, over a wide range of room index values and surface reflectivities. Further, using a digital computer he obtained values of these ratios for a large range of room parameters covering some 35,000 possible variations. Results[6] have been published for 160 different rooms.

(3.2) Glare rating

The variables which govern the glare condition in interiors have been known for some time, but extensive use of the available data has been delayed, because some of the related problems had still to be solved and also on account of the amount of work involved in the calculation for a large installation.

The calculation of the glare constant for a single source in an installation requires the following data:

(1) radial distance from the source to the observer's eye,
(2) orthogonally projected area of the source in the direction of the observer,
(3) luminous intensity of the source in the direction of the observer,
(4) position of the source in terms of the vertical and azimuthal angles to the observer's line of sight,
(5) luminance of the general surroundings.

Each of the items 1–4 will have a different value for each source in the installation, and these must be determined separately. The glare constant for the installation is taken as the sum of the glare values for the individual sources.

A simplification can be introduced by determining glare constants for unity background luminance, since items 1–4 are independent of surface reflectivities and luminance, and are related only to the geometry of source position, source area and luminous intensity distribution. Even this requires at least sixteen separate steps to determine the glare constant for one source; thus in an installation of 100 luminaires, one is required to make 800 separate calculations for the single case of unity background luminance.

The urgent need to predetermine the glare rating for installations has led to the request for general guidance, using simplified methods or tabulated data covering a wide range of the variables. The Luminance Study Group of the IES Code Panel considered this problem, and it was agreed that a full investigation should be carried out.

The relative importance of the factors affecting glare in multiple-source installations, and the size of the steps in the tabulated values necessary to give a useful range of data had to be studied. It was necessary to determine the glare ratings for a range of luminaire distributions, a calculation only practicable using a digital computer.

The problem was prepared for the computer office in the following form.

For a complete installation:

$G = G_1 + G_2 + G_3 \ldots + G_n$,

where G_1, G_2, G_3 etc. are the glare constants for each source of the installation.

For a given fixed position of the observer the general formula is:

$$G_n = \frac{B_s^{1.6}\,\omega^{0.8}}{B_b\,P^{1.6}}$$

where B_s = luminance of the glare source in foot-lamberts, ω = solid angle in steradians subtended by the source at the observer's eye,
B_b = surround luminance in foot-lamberts,
P = source position index.

The formulae can be written:

$$G = \frac{(\pi I_o)^{1.6}}{B_b} \cdot \left[\frac{K_1^{1.6}}{A_1^{0.6}} \cdot \frac{1}{d_1^{1.6}} \cdot \frac{1}{P_1^{1.6}} + \frac{K_2^{1.6}}{A_2^{0.6}} \cdot \frac{1}{d_2^{1.6}} \cdot \frac{1}{P_2^{1.6}} + \dots \right]$$

where K varies with the angle of elevation and direction of the source, and is dependent upon the intensity distribution of the source.

I_o is the source intensity in candelas in the vertically downwards direction,

A is the projected area of the source in sq. ft. in the direction of observation.

In many cases the area A may be resolved into three components related to the areas A′, A″ and A‴ in the directions normal to each of three surfaces, one facing vertically downwards and two facing horizontally at right angles to one another. Thus:

$$A = A' \cdot \frac{h}{d} + A'' \cdot \frac{x}{d} + A''' \cdot \frac{y}{d},$$

where x and y are the co-ordinates of the source plan position, h the height of the source above the observer's eye level, d the distance from the source to the observer's eye.

Position index P is read from a table, stored in the computer, which was prepared from the position index chart,[7] the values being in terms of h/y and x/y.

The above basic data make up the programme used to determine the operations to be carried out by the computer. For any given problem the information which has to be sent to the computer office are values of B_b, I_o, A′, A″, A‴, and h: the spacing and number both of sources in each row and of rows in the installation: and a table of values of K (taken from the polar curve of intensity distribution). Individual glare source ratings and running totals are then provided by the computer.

A large quantity of data is now available for further study, covering a large range of room dimensions and twenty different luminaire intensity distributions.

In preparing the computer programme the concern was basically with the IES investigation, but the programme can be used to determine glare ratings for any specified set of conditions in future routine calculations.

(3.3) Street lighting studies

The performance of a street lighting installation involves the installation itself, the road surface reflection characteristics and the motion of the observer. It can be assessed in terms of road surface illumination, road brightness from the driver's viewpoint, glare and revealing power based on the requirements established by the experimental work[6] of the Ministry of Transport Departmental Committee on Street Lighting prior to publication of their Final Report in 1937. A programme was developed to calculate these data for varying light distributions, quantity of light, mounting height and spacing of lanterns for three common road surfaces of widely differing reflection characteristics, using data for these determined by Road Research Laboratory, DSIR, and a paper including results was presented to the APLE Conference[8] in September 1957. Later the programme was extended to determine revealing power, taking veiling or disability glare into account.

Data are calculated for points in rectangular formation, spaced at 30 ft intervals along the road and 5 ft across, the central row coinciding with the road axis from which transverse distances are measured, as shown in Fig. 6. Measurements along the road are from the driver's position, that agreed

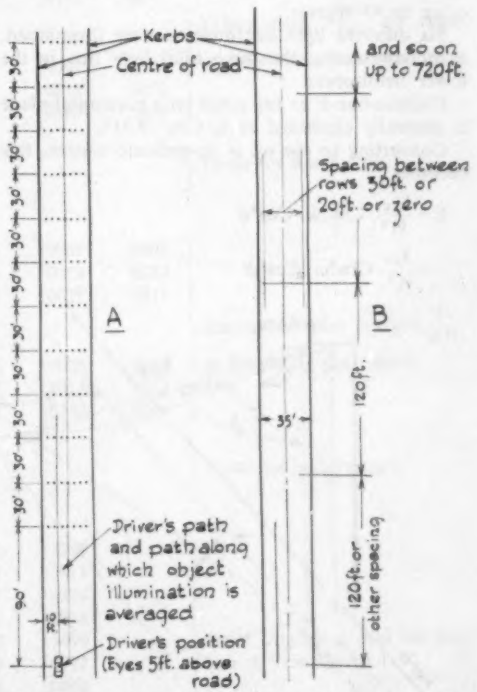


Fig. 6. Calculation of street lighting performance. (A) Section of road showing points for which illumination, road brightness, etc., are calculated for the driver's position shown. (B) Section of a typical installation which is superimposed on (A) and moved along relative to the driver in steps simulating his progress through the installation.

by CIE in 1935; and with seven lines of points the total road width is 35 ft between kerbs.

(3.3.1) *Illumination on roadway*

Road illumination from one lantern is calculated for grid points in rows up to 360 feet away, and stored. Lantern light distribution, arrangement and mounting height are involved; referring to Fig. 7, H is the mounting height of the lantern above the road surface, and x, y are the differences in co-ordinates between the plan position of the lantern and the point at which illumination is being calculated.

When the programme was prepared the interest was in horizontal line sources transverse to the road. For these the intensity $I_{\omega\psi}$ in direction ω, ψ (see Fig. 7) is closely equal to $I_{\omega o}$. $\cos^2\psi$ (where $I_{\omega o}$ is the intensity in direction at angle ω to the downward vertical in the plane $\psi=0$), and it was possible to specify the whole of a lower hemisphere light distribution by means of a table of $I_{\omega o}$ for values of ω up to 90 degrees.

Six different light distributions were formulated, each representing the same total light flux in the lower hemisphere.

Illumination E at any point on a horizontal plane is generally expressed as $I_\theta \cos^3\theta/H^2$.

Converting to the ω, ψ co-ordinate system, this becomes

$$E=\frac{I_{\omega\psi}}{H^2}.\cos^3\omega.\cos^3\psi$$

$$=\frac{I_{\omega o}}{H^2}.\cos^3\omega.\cos^5\psi$$

As it is more expedient to work algebraically than in terms of trigonometrical functions, this formula was used in the form

$$E=I\omega_o\frac{(H^2+x^2)\,H}{(H^2+x^2+y^2)^{\frac{5}{2}}}.$$

Contributions from all lanterns in the given arrangement are totalled and printed for each point. A specimen tabulation is shown as Table 1, the first row of figures corresponding to the row of points across the road adjacent to a nearside lantern column.

The illumination values for a single lantern were retained in store for the calculation of road surface brightness.

(3.3.2) *Glare*

For both veiling glare and discomfort glare, illumination on the driver's eyes is first required: the geometry is similar to that already outlined, reducing to

$$E=I_{\omega o}\frac{(H-5)^2+x^2}{[(H-5)^2+x^2+y^2]^2}$$

Veiling glare (B ft-L) is calculated using the Stiles-Holladay [10] formula:

$$B_v=\sum\frac{kE}{\theta^n}$$

where E is the illumination on the driver's eye from a light source, in lm/ft²,

θ is the angle in degrees between the direction of view and direction of the source,

and k and n are given their generally accepted values of 10π and 2 respectively.

This glare figure is calculated and printed for

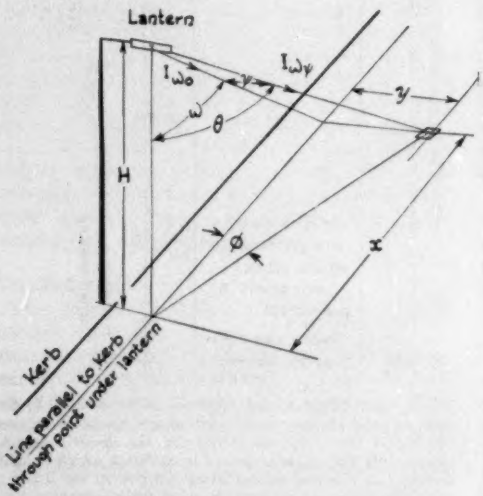


Fig. 7. Calculation of street lighting performance—angles relating to illumination.

Table 1

Specimen of Results of Street Lighting Performance Calculation

As printed on the computer output, with explanatory notes added.

27.7.60—50								
L1 DATA24								Installation Data
LANT.B	H=25·0	W=30	S=120					–Light Distribution Mounting Height Width and Spacing
1·883	1·715	1·322	0·911	0·596	0·390	0·264		
0·834	0·809	0·732	0·626	·0515	0·414	0·331		
0·361	0·378	0·388	·0392	0·388	0·378	0·361		Illumination on Road
0·331	0·414	0·515	0·626	0·732	0·809	0·834		
0·264	0·390	0·596	0·911	1·322	1·715	1·883		
0·145	0·270	0·441	0·538	0·156	0·305	0·567	1·020	Illumination on front of object
N.S.								
·0079	·0080	·0081	·0082	·0084	·0085	·0086	·0087	
·0088	·0089	·0090	·0092	·0094	·0096	·0099	·0106	
·0118	·0128	·0150	·0196	·0313	·0502	·0481	·0297	
O.S.								Veiling glare, $\frac{10\pi E}{\theta^2}$, for single
·0038	·0039	·0039	·0040	·0040	·0041	·0041	·0042	nearside and offside lanterns
·0042	·0043	·0044	·0044	·0045	·0046	·0048	·0051	
·0056	·0061	·0071	·0091	·0143	·0220	·0190	·0083	
·0513	·0604	·0600	·0546					Totals for installation
·0627	·0826	·0820	·0665					
N.S.								
·0005	·0005	·0006	·0006	·0006	·0007	·0008	·0008	
·0009	·0010	·0011	·0012	·0014	·0016	·0018	·0022	
·0028	·0036	·0052	·0084	·0177	·0404	·0625	·0811	
O.S.								Discomfort glare factor S, $\frac{E_v}{\theta^{\cdot 75}}$
·0004	·0004	·0004	·0005	·0005	·0005	·0006	·0006	as for veiling glare above
·0007	·0007	·0008	·0009	·0010	·0012	·0014	·0017	
·0021	·0027	·0038	·0061	·0126	·0272	·0370	·0313	
·0183	·0341	·0458	·0438					Totals for installation
·0220	·0465	·0701	·0916					
VP.A								
·3875	·3687	·2370	·2164	·2715	·2297	·2017		
·1987	·2119	·1778	·2246	·3501	·3911	·3813		
·2092	·2375	·2090	·2598	·4085	·5105	·4399		
·1855	·2322	·2034	·2501	·3778	·4592	·2918		
·2335	·2679	·2265	·2606	·3640	·3253	·1650		Road brightness data for Sur-
·4029	·4020	·2715	·2217	·2498	·1598	·0892		face A/ Viewpoint A
·4558	·4617	·2727	·2186	·2055	·1281	·0869		
·3493	·3933	·2326	·2115	·1587	·1124	·0941		
·2076	·2947	·1817	·1898	·1571	·1642	·1653		
·1116	·1901	·1664	·2085	·2876	·3266	·2608		

(*Continued on next page*)

VP.B							
·4571	·4179	·2557	·2173	·2583	·1930	·1395	} Row 360 ft. ahead of driver
·3738	·3629	·2304	·2118	·2738	·2239	·1951	
·1941	·2118	·1781	·2255	·3410	·3874	·3767	
·1961	·2331	·2069	·2612	·4051	·5075	·4265	
·1763	·2305	·2026	·2573	·3833	·4342	·2653	
·2284	·2666	·2260	·2733	·3729	·2925	·1494	
·3929	·3978	·2678	·2253	·2422	·1405	·0803	
·4299	·4474	·2610	·2058	·1631	·1077	·0785	
·3104	·3745	·2196	·2025	·1335	·1034	·0874	
·1501	·2469	·1546	·1410	·1363	·1542	·1593	Row 90 ft. ahead of driver

single nearside and offside lanterns at distances from 720 feet ahead down to 30 feet ahead, providing a useful indication of which lanterns cause most glare. Contributions are then summed and printed for any selected arrangement of lanterns, starting from a viewpoint adjacent to a nearside lantern. The appropriate value of veiling glare is taken into account when calculating revealing power.

Assessment of the discomfort glare is made in terms of the effect of the light from the lanterns on the driver's eyes when they are adapted to the prevailing road brightness. Hopkinson's[11] formula determines a glare constant c in terms of road luminance, total for all lanterns of eye illumination weighted according to the direction of each lantern in relation to the direction of view, and the luminance of the lanterns. This weighted eye illumination $\left(\frac{E}{\theta^{0.75}}\right)$ is calculated and printed as for veiling glare, so that c can be calculated for a particular viewpoint using any chosen source luminance and the appropriate value of road surface luminance.

Neither veiling nor discomfort glare values were averaged in the computer; this would have saved a little effort later, but an important aim was the study of the fluctuations as the driver travelled through the installation.

(3.3.3) *Road brightness*

It would not have been practicable to calculate road surface luminance for a number of viewpoints throughout an installation without the aid of a digital computer; even the computer takes 15 to 30 minutes for one road surface and one set of variables. With the best of desk calculators the calculation would take one or two months, and graphical methods would be little quicker.

Road surface reflectivity β is a compound of specular and matt reflection; consequently the reflectivity at a single point varies by several log units according to the direction of the incident light and the direction of view. For each point it must be determined for each combination of lantern and observer position.

Christie[12] has shown that certain approximations can reasonably be made, and specifically that

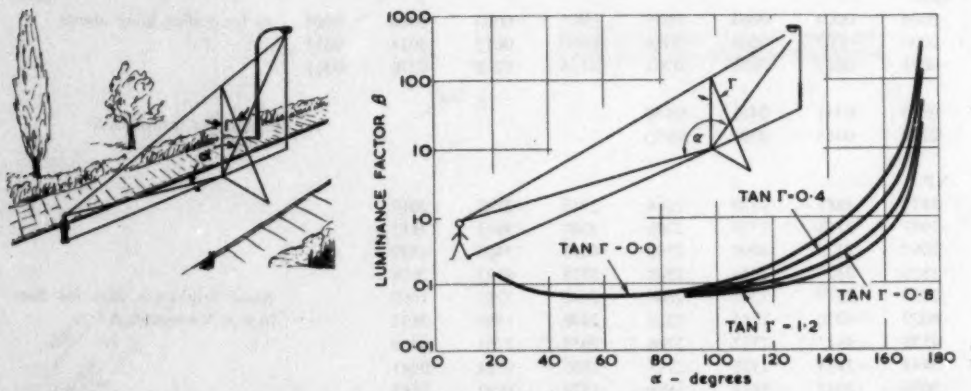


Fig. 8. Left, definition of angles α and Γ used in handling road surface reflection characteristics. Right, reflection characteristics of dry rolled asphalt surface, with precoated chippings. (B.S. 594). (From 'Light and Road Safety' by Sir William Glanville, Trans. Illum. Eng. Soc. (London) **25,** *No. 2, 1960).*

reflectivity can be related to two angles α and Γ of Fig. 8. The second angle Γ is required only when α exceeds 90 degrees.

For each viewpoint the programme considers each point of the grid in turn, calculating α (and Tan Γ if necessary) for each lantern, and then using a two-way interpolation subroutine to read the value of β from Christie's data, reduced to a tabulation of values of β for values of Tan $\Gamma = 0, \cdot1, \cdot2$ etc. and values of α at every 5 degrees from 30 to 180 degrees. The value of β is multiplied by the illumination at the point from the lantern concerned, and the product is added into the total for the point for the appropriate observer's position. The results are printed out in blocks labelled with the driver's position, the table being inverted so that the bottom row corresponds to the foreground points 90 feet ahead and the top row to those at 360 feet ahead (see Table 1).

(3.3.4) *Revealing power*

An alternative version of the programme was prepared to calculate and print revealing power instead of road brightness.

Harris and Christie[12] have shown that variation of illumination across the road can be neglected, and for one full cycle of a Group A installation can be averaged (E_m) to give a valid approximation of revealing power. The geometry of the calculation of object illumination is similar to that for road illumination, reducing to:

$$E = I_{\alpha\phi} \frac{[(H-2)^2 + x^2]\, y}{[(H-2)^2 + x^2 + y^2]^{\frac{5}{2}}}$$

This is summed for all adjacent lanterns up to 300 feet away, for positions at 30 feet intervals on the line ahead of the driver; the sums are printed and then averaged.

Dunbar's data in the form of a graph of object brightness (B_o) for minimum necessary contrast against a range of background (road) brightness are stored as a table of object brightness for values of background brightness; Smith's data from a graph of percentage of pedestrian clothing of less than a given reflectivity against that reflectivity is treated similarly. The driver sees veiling brightness (B_v) superimposed on both object and background; its effect is taken into account by adding its value to that of the background brightness before referring to the table of Dunbar's data, then subtracting it from the value read to give B_o, the maximum object brightness seen with adequate contrast. Dividing this by the average vertical plane illumination gives the maximum reflectivity value for adequate contrast; approximate revealing power is read from the table of Smith's data, as the (probable) percentage of pedestrian clothing of equal or less reflectivity.

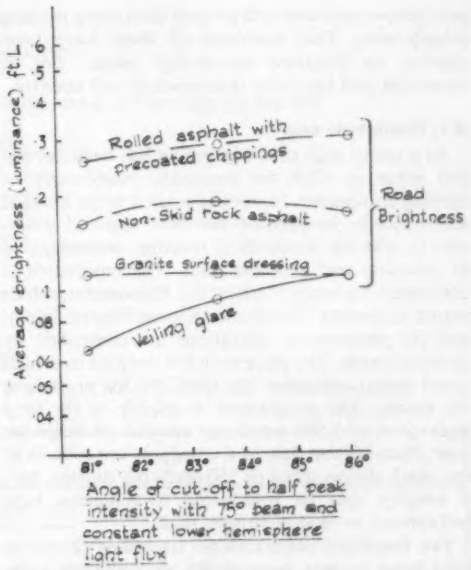


Fig. 9. Street lighting performance—a graphical presentation of one important result. For road surfaces of the measured reflection characteristics 'high angle' light increases glare with little or no increase in average road brightness. The calculations on which this diagram is based show the brightness distribution on each surface for a series of driver positions.

(3.3.5) *Street lighting performance*

The results from these calculations provided a valuable indication of which factors can most effectively lead to improved street lighting performance; for instance Fig. 9 shows the suitability of different light distributions for modern road surfaces. With a constant light flux in the lower hemisphere, while road brightness increases on the shinier surface as more light is directed at higher angles, the effect for rougher surfaces is to increase glare. Mathematical analysis of the component factors is more decisive in some cases than trial installations, where it is difficult to keep other conditions constant so that the effect of the one variable can be appraised. The programme was also useful in providing data for judging the optimum size and the best methods of applying linear sodium lamps.

(4) Examples of Computer Techniques in Routine Applications

The Computer Centre includes programmers and

production staff who will process data using existing programmes. Two examples of these have been selected to illustrate day-to-day usage; one is American and the other developed in this country.

(4.1) Photometric data

At a rather high cost, equipment has been devised and made in USA for automatic photometry of lighting equipment. It was considered to be justified economically, because of the time required otherwise to take the hundreds of readings necessary and to calculate and plot the data. The equipment is christened PAUDGET [14] (short for Photometer, Automated Universal Distribution Gonio Electric Type), and its photometric operations are controlled by punched cards. The photometer is coupled to a high speed digital computer, the IBM 704, for processing the results. The programme is read in at the very high speed of 2,500 words per second on magnetic tape. Photometric data and constants are read in at the much slower speed of 150 cards per minute, but, if lengthy, can be transferred to magnetic tape beforehand to save computer time.

For floodlight projectors the computer calculates total beam lumens, beam width etc., which is quite commonplace. In addition it 'draws' isocandle diagrams by means of cathode ray tube and camera, complete with labelling and grid lines, in 23 seconds.

There would be considerable advantage in time and cost if photometric data from present photometers were processed by computer; it would be reasonable to provide more complete data on lighting equipment. So far as is known this has not yet been done in this country.

(4.2) Area floodlighting calculations

For small floodlighting installations it is possible, on the basis of past experience, to judge the number of projectors that will do the job, adding projectors later if necessary. Larger installations, involving expensive high towers and cabling, need accurate planning. Usually the customer has indicated where the floodlights can be mounted, and has specified the illumination and area to be covered. The spherical chart[15] permits a graphical method of design, but the planner tends to spend time going over the scheme again to find any points that he may have overlooked.

In 1958 a programme[16] was constructed which carries out point by point calculations quickly and accurately. The lighting engineer chooses a rectangular grid (see Fig. 10) to cover the area to be checked, and gives data on the floodlights aimed on the area: the programme is designed to calculate the horizontal plane illumination at the centre of each unit of the grid. Eight units across are calculated and printed at a time, because this conveniently fills a line across the page, and up to 100 such lines can be dealt with at a time. By specifying a small grid and repeating the process, the area can be checked as closely as required.

Data are passed to the computer office in the form shown in Table 2. The title of the installation and the dimensions of the grid are specified, and below are tabulated data on the floodlanterns; the data which change from one floodlantern to the next are given in the early or lefthand columns, in order to save tape and tape-punching time, as only changes in data from the preceding line need to be punched,

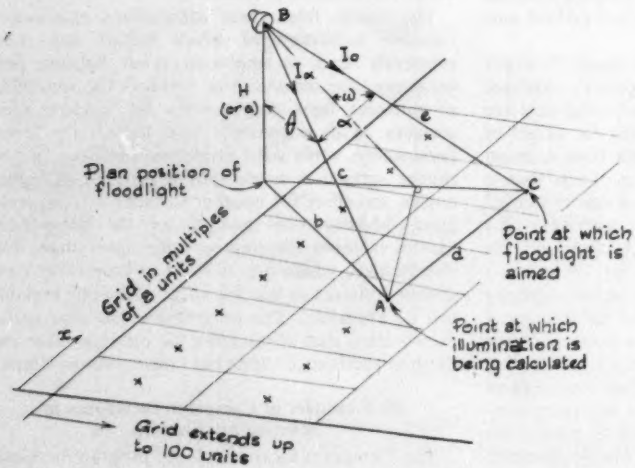


Fig. 10. Illumination under area floodlighting—specification of a grid to cover the area concerned and geometry of calculation of illumination from a symmetrical beam floodlight.

Table 2

Computer Data Sheet

D
N
L3/L4 Data
Input by I.O. ....ABERDEEN TOWER D .....
....JFP/LEICESTER.....
Title
Initials/Region
Blank tape
T31.0

Programme L3. Performance of Floodlighting Systems

Charging Number.....

Additional Requirements.....

GRID DATA

Section Width 30 ft × 10^{-4}	Section depth 30 ft × 10^{-4}	No of rows (down)	No of pages of 8 cols (across)
+.003	+.003	+12	+1

J2.0 LANTERN LIST

Target point x	Target point y	Mounting Height	Code No. for distr.	Cut-off 10^4 Tan β	factors 10^4 Tan γ	Location x	Location y
37	50	110	386	0	0	−63	−31
80	50	→					
27	147	110	332	→			
37	114	→					
37	180	→					
37	245	→					
137	310	→					
80	114	→					
80	180	→					
80	245	→					
80	310	→					
100	16	→					

Input by R116 (modified)

Continued

(1) Continue on separate sheets, as necessary, and end with an asterisk on a separate line.
(2) All numbers on the lantern table must be integers, and positive signs may be omitted.
(3) An arrowhead may be used to indicate that the remainder of a line is unchanged from the line above.

followed by a sign indicating 'remainder unaltered'. Then follows the mounting height of the floodlantern, and a reference to the computer store location where the appropriate light distribution table will have been read in. Next are two columns giving necessary data (tan β or tan γ as indicated in Fig. 11) if horizontal or vertical louvres are fitted to the floodlantern, or a zero if not, so that the relevant part of the programme is jumped. The last columns give the co-ordinates of the plan positions of the floodlanterns.

As each line of floodlantern data is read, the programme effects calculation of the illumination at the centre point of each grid unit in turn, keeping a running total for each point, and printing out totals when the end of the list is reached.

The geometry of the calculation is illustrated in Fig. 10.

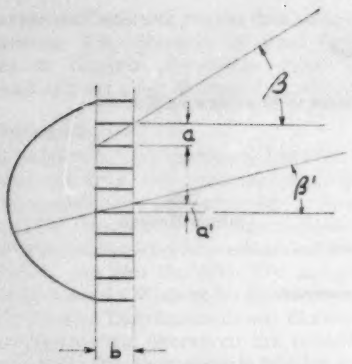


Fig. 11. Illumination under area floodlighting—vertical cross-section of floodlight showing effect of horizontal louvres.
At $\beta = \tan^{-1}\frac{a}{b}$, *cut off is complete*
At β^1 (*where* $\beta^1 < \beta$) *cut off is* $\frac{a^1}{a}$, *the fraction of light transmitted* $= \frac{a-a^1}{a}$
For vertical louvres the angle corresponding to β *is labelled* γ.

Illumination at A due to projector at B aimed at C is given by:

$E_A = I_\alpha \cos^3\theta / H^2 = I_\alpha . a/c^2$,

and $I_\alpha = f(\alpha)$.

α is determined by the cosine rule from the values of a, b, c, d and e; and to save time the polar curve table is given in terms of values of Cos α instead of α. The steps of Cos α have been graded, using small intervals over the beam and large intervals in the stray light zone where changes are slower. If α exceeds 60 degrees it is assumed that there is no contribution from that floodlight and the computer steps on to the next point: this has often made considerable reduction in computer time.

If louvres are fitted the light distribution is modified by a factor dependent on the spacing 'a' and depth 'b' of the louvres (see Fig. 11). Assuming that over spacing 'a' the parallel elements of reflector contribute equally to the beam—which is reasonably true on average—and neglecting the thickness of the louvres and reflection from their surfaces, the reduction in intensity at angle β' off axis is $\frac{a'}{a}$, where $a' = b \tan \beta'$. Thus the intensity with louvres will be $I_\alpha . (\frac{a-a'}{a})$ at angle β', or $I_\alpha . \frac{(\tan\beta - \tan\beta')}{\tan\beta}$, where $\tan\beta = a/b$.

The latter form is convenient, as tan β is the ratio of spacing to depth of the louvres and tan β' is tan ω of Fig. 10. It is now necessary to calculate the value of ω as well as angle α, but the computer takes this in its stride. This part of the programme is doubly useful as the effect of spreader glasses can be approximated in the same way.

The original programme can be used to calculate illumination on any vertical plane parallel with the datum lines of the grid, by substituting for H the length of the normal from the plane to the floodlight and recalculating the co-ordinates of floodlight aiming points on a new grid on this vertical plane. Other vertical planes can be dealt with, but a further pre-processing would be needed to transfer to datum lines parallel to the required planes; so far the need has not arisen.

The programme has also been used to give data on illumination from single standard types of projector at a range of angles of aim, but little use has been made of these results.

(5) Conclusions

During the past three years electronic computers have ceased to be a novelty, and scores are in daily use; in this short review we have attempted to show how they have enabled an advance to be made in general lighting practice.

In the research and development laboratories they have already enabled the progress of lamp and lighting design to be pushed forward a significant step, by helping the physicist to understand some of the processes of low pressure discharges,[17] which has helped the development of non-cylindrical tubes for higher-loading fluorescent and sodium lamps.

Once a large scale study has been undertaken with the aid of a computer, many results may be communicated in a very much simpler form for the direct application of the lighting engineer; when all the work carried out by O'Brien on 35,000 rooms has been assimilated, it may render unnecessary much tedious calculation. Assistance with calculations of interreflections and glare should result in the next IES code showing a material advance towards designing improved installations. Some of the laborious calculations of lantern photometry are being eased and speeded; and, as in the application to area floodlighting, the practising lighting engineer can obtain economically a complete calculation of his design.

Simple direct analogue computers help to show the effects of controlling the variables for certain lighting installations, but the major tool is the digital computer, which, by taking out the drudgery, should enable the design engineer to use his talents more effectively.

(6) Acknowledgments

Much of the work described in this paper would have been impossible but for the encouragement of

the AEI directors and the enthusiastic collaboration of Mr E. A. Allwright and his staff in the Engineering Mathematics Department at Rugby.

The authors also acknowledge with thanks the kindness of the Director of Road Research in making available unpublished data, and the help of many colleagues in the AEI Lamp and Lighting Co headquarters at Leicester.

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Appendix 1

Example of programming a digital computer

Computer manufacturers have introduced simplified programming procedures which, though working less efficiently as regards speed, enable a novice to programme a straightforward problem and operate the computer after only a few hours training. For brevity a rather more trivial problem than would normally be referred to the computer is used here as an illustration of programming by such simplified methods.

Problem:

A light source, giving uniform intensity I(cd) in all directions, is mounted H (feet) above a horizontal surface. Programme calculation of illumination on the plane normal to the direction of incident light for points at intervals of D (feet) from the point below the source up to a distance of 10 D, and tabulation of results to two decimal places.

When the programme is used a data tape will supply specific values of I, H and D for each run of the programme.

The lighting engineer will inform the programmer that the illumination at point x from below the source can be calculated as: $E = I \times \frac{\cos^2\theta}{H^2}$ where $\theta = \tan^{-1}\frac{x}{H}$.

The programmer will decide that for the computer the most suitable form of the formula is:

$E = \frac{I}{H^2+x^2}$, where x takes the values of n.D for n=0 to n=10.

The programmer starts by drawing up a flow diagram, on which the programme of instructions will be based without any variation. He will begin at the core of each separate stage of the calculation, then combine the stages or subroutines into assemblies and finally into the complete programme.

In our example the flow diagram, for simplified code working might be:

1. Read in from data tape and store values of I, H and D.
2. Print these in a line under the heading of the result sheet.
3. Calculate H^2 and store in place of H.
4. Set up counter to give consecutive numbers for n.
5. Read number of n.
6. Multiply n by D and store.
7. Evaluate $(nD)^2$ and store.
8. Add H^2 to give $(H^2+(nD)^2)$.
9. Divide $(H^2+(nD)^2)$ into I to give E.
10. Print E in required arrangement.
11. Add 1 to value of n.
12. Test if n=11.
13. (a) If NO return to step 5 and repeat.
    (e) If YES return to start of programme.

Most of the Pegasus Autocode instructions below call in a subroutine or series of orders from the built-in programme; that need not concern the novice programmer or lighting engineer. Referring to the Table of Instructions, he can write the programme as follows:

Programme

Tape	*Notes*
D	Instruction to print date and serial number for day at head of result sheet.
N	Indication that the 'name' of the programme which follows is to be printed as heading to result sheet.
ILLUMINATION FROM UNIFORM SOURCE	Heading for result sheet.
J1.0	Instruction to enter simple code working.
STOP	Order which is read into store for present: it will stop computer in the 'Ready' position when the whole programme has been read in and the computer starts to follow the orders sequentially.
$v0$=TAPE3	Order to read three numbers from data tape, and store in 'variables' store locations 0, 1 and 2.
PRINT$v0$,3140	Order to print out value of $v0$ under heading. This is the value of I which has just been read in. This and the values of H and D serve to identify the particular result sheet. The '3140' is an instruction to print on new line, up to seven digits before the decimal point; none after.
PRINT$v1$,4061	This calls for printing of the value of H, stored in $v1$, on same line as previous figure, with up to 3 figures before decimal and one after.
PRINT$v2$,4041	This calls for printing of the value of D, stored in $v2$; same line, 2 figures before decimal and one after.
$v1=v1\times v1$	This calls for the value of H stored in $v1$ to be squared and stored in $v1$.
$n0=0$	This calls for the 'counter' store location 0 to be set to an initial figure of 0. This number will serve both as a counter of the number of values for E that have been calculated and also as factor n in the term nD.
$1)v4=n0$	This order reads the count number in $n0$, giving the factor n in location $v4$. 1) is the label which enables the programme to return to this order when beginning to calculate E for the next value of n.
$v4=v4\times v2$	Multiplies number in $v4$ by that in $v2$, giving $n\times D$. Stores result in $v4$.
$v4=v4\times v4$	Squares nD (from $v4$) and stores result in place of nD in $v4$.
$v4=v4+v1$	This adds H^2 into $v4$, giving $[H^2+(nD)^2]$.
$v4=v0/v4$	Divides I (from $v0$) by $[H^2+(nD)^2]$ from $v4$, and stores the result (which is E) in $v4$.
PRINT$v4$,3082	Prints E from $v4$, on new line with 4 figures before decimal point and two after.
$n0=n0+1$	Adds 1 to figure in counter store location 0.
$-1,n0\neq 11$	Jumps back to instruction labelled 1), unless eleven values have been calculated.
(-0)	Jumps back to beginning of programme, i.e. to STOP order, where computer waits for another data tape or a fresh programme.
XXXXX	Identification to prevent the tail of the tape being fed in first by mistake.

Data Tape

+1860	First number is the value of I.
+23	Second number is the value of H.
+18	Third number is the value of D.
Z	Order to stop after reading data tape.
XXXXX	Identification of end of tape.

Discussion

MR W. ROBINSON: I feel that one has to be careful not to be blinded with science. It seems wrong to regard computers with awe, indifference or antagonism. I used to feel that the computer might well be used as a substitute for brains, but that was before I had any real experience of what a computer could do. I must say I still don't understand the things.

As Chairman of the study group I was given the job of producing glare indices in the new Code; I did not realize when I received the calculations that I was getting something like two man-years of labour or I should have been even more grateful than I was. I have unbounded admiration for what the computer and its programmer have done for us. I realised it was the function of the computer to make possible the tackling of problems which otherwise would lie on the shelf. At the time we were not really in a position to use the computer to its full capacity.

We did get what we asked for, but we did not ask for enough; we still had to calculate adaptation luminance. If we were going to do the job all over again we would feed the whole thing into the computer, and I am sure the computer would produce the answer.

The thing which interests me about this paper is what it implies rather than what it has told us. There are two stages, first the programming and then the anlysis of the results; the presentation and use of the results presents the real problem. The computer must be worked very hard; but the more you feed into a computer the more you get out, and the volume tends to be indigestible and needs to be sifted into a form which non-mathematical people can use in their everyday work.

We have avenues opened up which we have never had before; but we are no better off unless we know in the first place what we want to find out. Luminance can be calculated for any room, but the results are meaningless to a large number of people; to some extent the same applies to the computer's work on revealing power, which is splendid, but revealing power calculated to four decimal places has little value as such. It is very much easier to calculate than to know what to calculate or how to use the result of the calculation.

The computer is here to stay for floodlighting etc.; it is likely to become standard equipment in illuminating engineering and I am very happy to see this. This machine is the last link in the chain but is no use without the other links. The very fact that, through O'Brien's work, luminance data are available for 35,000 rooms is an encouragement for us to discover the subjective significance of luminance differences. I hope we shall see a drive on those matters about which in the past very little has been done in the way of application largely because these data were not available. Difficulty of calculation need no longer be considered as a barrier to the commercial use of research information; but let us be quite sure that, while knowing that 2 and 2 make 4 and not 5, we also know the difference between 4 and 5.

MR P. PETHERBRIDGE: This evening we have been treated to a series of quite remarkable demonstrations which have explained in a very clear fashion many of the technicalities referred to in the written paper; binary coding, the 'mill', etc., begin to take on a real meaning for us. It is a fact that the calculations which automatic computers perform are not nearly as complex as would at first appear; the speed at which the computers operate gives them their mystical character. Those of us who use a desk calculator know that the machine works by a series of simple additions and subtractions; automatic computers merely do this on a grandiose scale.

My interest in the application of automatic computers has been to the calculation of glare indices. I was at first a little disconcerted to learn that a single manipulation of the BRS glare formula requires sixteen items of information to be fed into the computer; I have, however, reassured myself that this is in fact so. Having had some recent experience of applying the glare formula to a number of large lighting installations, I would have welcomed the assistance of one of the computers described to us this evening.

I am privileged to have worked closely with Mr Robinson's Luminance Study Group on the projected glare tables, and I was impressed by the way the Position Index data could be handled by the computer. As published by Luckiesh and Guth, these data take the form of a series of curves. To programme the computer, Mr Bellchambers has laboriously compiled from them a table of Position Indices, the computer automatically performing a series of cross-interpolations to obtain the required values.

The work reported this evening has been concerned almost entirely with lighting design; computer techniques can, of course, also be applied to the analysis and automatic recording of the results of research work. Over the past twelve years a considerable number of discomfort glare studies have been carried out at the Building Research Station, resulting in an enormous amount of data recorded in the laboratory observation books; these data have been referred to on numerous occasions and fresh analyses made. If at the outset, the data had been recorded on punched tape or cards, as is being done now in connection with the large-area glare source work on which we are currently engaged, a lot of repetition would have been avoided in the subsequent analyses.

The application of automatic computer techniques to lighting calculations holds great potentialities. The user will, however, have to hold this new tool in close check or else be overwhelmed by reams of figures with which he cannot possibly cope.

Mr Robinson has referred to Professor O'Brien's paper; at least five pages of this paper were compiled by the computer itself. Perhaps in five years' time, Mr Ruff and his colleagues will present to the IES the first paper compiled entirely by a computer.

MR S. S. BEGGS: I found the paper very interesting to read, particularly the part on computers because I am one of the uninitiated. Although the illuminating engineer may know how they work, I take it that Mr Ruff did not mean that we ought to be able to work them.

The computer can be valuable in basic research work, because in most of the problems the factors have to be varied one at a time and for this purpose the computer is very useful. I am not quite so sure that it is likely to be of value in daily routine. In the USA there is a tendency to produce a mass of information, a great deal of which will never be used, and this seems to me a complete waste; I hope we shall not have this here as the authors suggest.

The crux of floodlighting installation design is the planning, not the calculation. The real work is done by the lighting engineer in deciding where he will direct the floodlights, and this is the bit the computer cannot do. How often does the lighting engineer re-plan a floodlighting scheme in the light of what the computer says? The problem is not usually so detailed; for example, a factor which cannot be included is the variation in floodlights, since you feed in data for an average floodlight. A computer will reveal a gross error but is quite costly. What is the cost of such a check?

The authors refer to the alternative of model room experiments; I should be interested to know how the model and computer results compare with actual installation values in practice, as both make assumptions (for example of uniform luminance), usually different for the two methods.

On the glare rating, the method of resolving the projected area by the direction cosines is ingenious; strictly it applies only to the box type of fitting of fairly uniform luminance, and I think perhaps has not got great application.

I was interested in the modification for the louvres which could be applied in area floodlighting calculations. The authors say the same programme could be applied to spreader glasses, but the effect of these is surely to give a more uniform distribution? I think one could prepare a technique on somewhat similar lines.

MR J. G. HOLMES: Whilst we are all impressed by the complexity of the construction and operation of computers we have to realise that they have no intelligence and can do no more than they are told. The skill lies in the brains of the programmer and of those who describe the programme to the programmer, who have to sit down and think out the details of the problem which the computer is to solve. For example, the mathematics of the inter-reflection of light within a room have to be understood and stated with clarity and precision if full advantage is to be taken of the accuracy which is possible with computers. It may be that in some problems this mathematical analysis is as difficult as the construction and use of a model or of an analogue computer, both of which have the facility that experiments can be made beyond the range of the original problem.

Can the authors tell us something of what is involved in instructing the programmer prior to the solution of a lighting problem, and whether it is possible so to programme a computer that it can be used for experimentation or to search for an answer which is unknown to the programmer?

MR A. G. SMITH: In the example of the use of computer technique for checking the design of an area floodlighting installation, it was shown that the illumination close to a tower was given by the computer as ·07 lumen per sq. ft., against a required minimum of 0·1. The calculations were simplified by feeding the computer with values of light intensity only for angles within 60 deg. of beam axis. On high towers it is normal for many of the floodlights to be aimed at about 75 deg. from the vertical, which would leave light up to 15 deg. from the vertical out of the calculation; in practice it is usual to find that the illumination builds up towards the base of the tower. It appears therefore that quite a little latitude is necessary in interpreting the check figures given by the computer.

DR R. G. HOPKINSON: It is important to remember that the computer is particularly designed to do a large number of routine calculations, which can be of great complexity but of no greater complexity than the basic equations fed into the computer by the programmer; then comes the problem of assimilating and understanding the results of the computer's calculations. A physical model of a lighting scheme is a far better analogue than an electrical analogue computer because the result of changes in layout, which would tax the electrical analogue's resources to quantify can be immediately comprehended in the model literally on sight. Even if a suitable analogue could be devised, it would tax our abilities to make sense of the results when they are presented in numerical form, which is all that the computer would be able to do.

For this reason I was able to give only limited support to Professor O'Brien's original paper on the use of analogue computers for lighting calculations. Perhaps it would be relevant here to point out that almost everything that the O'Brien computer can do can also be done on a slide rule such as the BRS Daylight Factor slide rule provided we are content to accept a less precise form of inter-reflection equation, still within the normal accuracy required in any practical lighting design.

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Will computers permit us to think in an entirely different way about our lighting problems since we are no longer handicapped by the thought of impossibly lengthy calculations? For example, most of my own researches have yielded a large amount of experimental information of great complexity because the eye and brain are complex entities; in order to make my experimental results useful to the lighting engineer I have always been faced with the difficulty of devising some simple formula to express them for practical use, although in specific circumstances it may be insufficiently precise. I would like to know whether the authors feel that I may now put out my experimental information in its original complex form, relying on the use of computers to do the lighting calculations, so avoiding the errors inherent in any simple formulation.

DR H. D. EINHORN: Do digital computers lend themselves easily to dealing with non-linear functions? The analogue computer might do this more easily.

THE AUTHORS (in reply); The discussion has shown generally a good appreciation of the fact that the usefulness of a computer depends greatly on knowing what data are needed to achieve an objective, and requesting from the computer only those data. The selecting of information from what would otherwise be a mass of unmanageable data is one main function of a computer; data can be stored and later analysed from any new viewpoint.

Graphical analysis of computer results can be most helpful, often leading to a better appreciation of the basic problem. This method gave a much clearer understanding of the pattern of changes in glare with changing light distribution and fitting luminance in large installations. Similarly, calculations combining data on road surfaces with the lantern and installation design were very extensive, but graphical analysis enabled the effect of each of the variables on the conditions experienced by a traveller through an installation to be appreciated.

In reply to Mr Beggs and Mr Smith, we have occasionally, although rarely, modified designs of area floodlighting installations after checking by computer; such a check is particularly valuable when illumination includes contributions from a number of adjacent towers. The illustration in the film was an example where from such calculation we could offer the user the planned scheme as a good approximation to his specification, advising him that whereas an extra floodlight would bring it fully to the specification its use could hardly be justified. We regret that the particular shot on the film was so short; otherwise it would have been clearer that it was at the extreme edge of the area remote from the tower where the illumination was 0·07 lm/sq ft instead of the specified 0·1 lm/sq ft. We have not yet had to include in our calculations the effect of a spreader glass; the programme is so constructed that interpolation between two polar curves could readily be made on the basis of the angles already calculated.

The answer to the question raised by Mr Holmes regarding the preparation of a problem and the instructions to be given to the programmer is given for a simple problem in Appendix I; more difficult problems are reduced to simple operations much the same as would be used in methods of calculation. Programmes can be devised to enable computers to search for optimum values from a given set of parameters. At present the design of area floodlight installations—as distinct from proving the designs as described in the paper—is too lengthy for linear programming techniques; with the development of higher computing speeds the method may possibly become more generally practicable.

Many non-linear functions can be programmed readily but, as implied by Dr Einhorn, handling of complex functions is cumbersome. When two quantities are related graphically, as is often the case with experimental results, they are stored as tables, the values required being extracted by interpolation programmes (or sub-routines) such as two-way linear or binomial interpolations according to the precision required. These subroutines are usually available from the computer manufacturer's library; unfortunately the method is lengthy in both time and storage space. Generally the situation is no easier with analogue computers. Where possible the relationship is best reduced to a formula, as was done in the treatment of louvres in the floodlighting calculations; similar attempts for the streetlighting calculations were unsuccessful.

The real limitation to the usefulness of O'Brien's analogue computer studies is a lack of information on the precise pattern of primary light distribution obtained from any given array of lighting fittings. Much is already being done to fill this gap in our

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Graphical analysis of computer results can be most helpful, often leading to a better appreciation of the basic problem. This method gave a much clearer understanding of the pattern of changes in glare with changing light distribution and fitting luminance in large installations. Similarly, calculations combining data on road surfaces with the lantern and installation design were very extensive, but graphical analysis enabled the effect of each of the variables on the conditions experienced by a traveller through an installation to be appreciated.

In reply to Mr Beggs and Mr Smith, we have occasionally, although rarely, modified designs of area floodlighting installations after checking by computer; such a check is particularly valuable when illumination includes contributions from a number of adjacent towers. The illustration in the film was an example where from such calculation we could offer the user the planned scheme as a good approximation to his specification, advising him that whereas an extra floodlight would bring it fully to the specification its use could hardly be justified. We regret that the particular shot on the film was so short; otherwise it would have been clearer that it was at the extreme edge of the area remote from the tower where the illumination was 0·07 lm/sq ft instead of the specified 0·1 lm/sq ft. We have not yet had to include in our calculations the effect of a spreader glass; the programme is so constructed that interpolation between two polar curves could readily be made on the basis of the angles already calculated.

The answer to the question raised by Mr Holmes regarding the preparation of a problem and the instructions to be given to the programmer is given for a simple problem in Appendix 1; more difficult problems are reduced to simple operations much the same as would be used in methods of calculation. Programmes can be devised to enable computers to search for optimum values from a given set of parameters. At present the design of area floodlight installations—as distinct from proving the designs as described in the paper—is too lengthy for linear programming techniques; with the development of higher computing speeds the method may possibly become more generally practicable.

Many non-linear functions can be programmed readily but, as implied by Dr Einhorn, handling of complex functions is cumbersome. When two quantities are related graphically, as is often the case with experimental results, they are stored as tables, the values required being extracted by interpolation programmes (or sub-routines) such as two-way linear or binomial interpolations according to the precision required. These subroutines are usually available from the computer manufacturer's library; unfortunately the method is lengthy in both time and storage space. Generally the situation is no easier with analogue computers. Where possible the relationship is best reduced to a formula, as was done in the treatment of louvres in the floodlighting calculations; similar attempts for the streetlighting calculations were unsuccessful.

The real limitation to the usefulness of O'Brien's analogue computer studies is a lack of information on the precise pattern of primary light distribution obtained from any given array of lighting fittings. Much is already being done to fill this gap in our

knowledge, and when the information is available the full usefulness of the analogue computer will be more apparent. Whether measurements on a model or variations of the parameters of a calculation can help most will depend upon the particular problem under investigation. The logical thinking needed for programming is helpful in itself. Dr Hopkinson and Mr Petherbridge have raised questions concerning the suitability of computers for research investigations; we feel that much labour could be taken from some of these by the help of digital computers. The point raised by Dr Hopkinson as to whether the use of the computer could reduce the need to simplify and approximate data before they could be applied practically is a most important one. While in some cases the results may need to be simplified, we feel that as experience grows in the use of computers the precise data, however complex, can be used directly. Not only would this help to remove doubts as to whether simplification has meant excessive approximation, but it would also facilitate the proving of newly-developed formulae.

Opinions have been expressed that the computer is less suited to routine calculations than research investigations. The authors' experience is that it can be equally useful in both fields.

THE SIXTH TROTTER-PATERSON MEMORIAL LECTURE

The Long-Range Forecasting Problem of Meteorology

By Sir GRAHAM SUTTON, C.B.E., F.R.S.

In the accepted terminology of professional meteorology, a 'long-range' forecast of weather is one which applies to intervals greater than a week ahead. Usually, the period selected is a month, but occasionally forecasts are attempted for a coming season. The official forecasts which, in this country, are put out several times every day by the Press and the broadcasting organizations are valid for 12 or 24 hours ahead with an 'outlook' which extends for a further 24 or 48 hours ahead; these are called 'short-range'. There is an intermediate category usually referred to as 'extended' or 'medium' range, which considers conditions over periods up to four days ahead.

I propose to confine my attention to the genuine long-range forecast, and in doing so the interval which I have chiefly in mind is one month. There is no particular significance in this selection of the period of the moon's phases, for weather is not related in any way, as far as we know, to the lunar calendar. It might be more appropriate to say 'a period of the order of tens of days', but a month is a useful word in this connection.

The problem to be discussed is therefore that of predicting the state of the atmosphere over a large region during an interval of time lasting for more than a few days. This does not imply an attempt to foresee the exact sequence of weather at any given place. I should regard the long-range forecasting problem as solved for most practical purposes if I knew of any method which could produce a statement like the following:

'. . . In the south east of England the coming month will begin with generally cyclonic weather, with temperatures 2° to 4° below average, rainfall about 25 per cent above average and fresh to strong winds. After about ten days there will be a change to settled anticyclonic weather, with temperatures a little above average, little or no rain, few clouds and generally light winds. This weather is expected to continue at least until the end of the period. . . .'

provided that it was verified on 80 to 90 per cent of occasions. The forecast would not be regarded as a failure if, say, during the expected fine weather spell, isolated showers were reported by one or two stations. The objective is a method of predicting accurately the *average* weather of a region during a prescribed period, and not its day-by-day sequence.

This point is of considerable importance and must be emphasized from the outset. The spatial inhomogeneity of weather, and particularly of rain, is so marked that most meteorologists regard its precise prediction at a given place for long periods ahead as impossible in principle. There is a useful analogy here with tidal theory. The oceanographer can predict the time of high tide along a stretch of coast with great accuracy and he can, within fairly close limits, say how high will be the general level of the water, but he cannot predict how far every wave will come up the beach. So it is with meteorology, except that, apart from seasonal changes, there is no regular periodicity in weather, and, as yet, we cannot even foretell with confidence more than the general level of any property of the atmosphere for considerable times ahead. Almanacs show the times of high and low water at all the principal harbours in the British Isles for all the days in the year, but they can say nothing about the maxima and minima of air pressure at these places, except as broad climatic averages.

The Nature of the Physical Problem

The concept of *climate* is well known and generally accepted as a valid generalization from experience. The climate of a region summarizes the average values of the meteorological elements during certain periods. (Usually, although somewhat unscientifically, the periods selected are the calendar months.) If the averages are formed from values obtained over long intervals of time, of the order of tens of years, the climate of a place is very nearly invariable. It is difficult to be certain of the reality of climatic change even over periods as long as a century. In the geological time-scale, the climate of the earth has undergone some remarkable changes, but in these instances we are dealing with intervals which, although relatively brief in the history of the rocks, are long compared with the span of civilization.

Although there has been a notable warming of

The Sixth Trotter-Paterson Memorial Lecture delivered at the Royal Institution, London, on 28th February 1961.

the Arctic and other parts of the Northern Hemisphere since about the middle of the nineteenth century, which may or may not be related to the increased production of CO_2 by the burning of fuels such as coal and oil, it is clear that, to a high degree of approximation there is now a long-term balance between incoming and outgoing radiation for the earth-sun system. The sun is the only significant source of heat for the atmosphere, but solar radiation is very unevenly distributed over the earth. On the average, net incoming radiation exceeds outgoing radiation from the equator to about latitude 40°, and the reverse holds from latitude 40° to the poles. Yet the tropics are not growing steadily hotter nor the polar regions colder, so that there must be a vast, highly efficient, global compensating mechanism at work. The compensation is brought about by the winds and also, but to a lesser extent, by ocean currents. The basic system of global winds, known as the general circulation of the atmosphere, must have many permanent features or else the observed stability of climate would not exist. This circulation forms the starting point for the scientific survey of the problem.

The problem of forecasting weather may be regarded mathematically as follows. At any given time the physical condition of the atmosphere over large areas of the earth (that is, the spatial distribution of pressure, temperature, humidity and wind) may be considered to be known as a result of observations made by the stations of the meteorological network. This is the 'initial state'. Subsequent major changes can, in theory, be predicted for short periods ahead by the use of the equations of physics, and it is obvious that in the short-range forecasting problem, the influence of the initial state must be very great. On the other hand, conditions averaged over very long periods must be independent of any particular initial state and must conform to the fixed entities of the problem, which are the configuration of the earth-sun system, the intensity of the incoming radiation (the solar constant) and the major topographical features of the surface of the earth, such as the distribution of land and water. This 'asymptotic solution' should bear a close resemblance to the general circulation of the atmosphere. The long-range forecasting problem, in the sense in which I have defined it above, is intermediate between the 'initial condition' problem and the 'asymptotic' problem. The sequence of weather over the next month is not independent of the weather today, but for such periods we cannot expect the details of the initial state of the atmosphere to impress themselves on the final state to any marked extent.

This was the view taken by the late Professor John von Neumann where he turned his attention to the problem of forecasting weather by mathematical methods soon after the end of the last war. Von Neumann brought the electronic computer into meteorology. His programme, in broad outline, was first to get reasonably good results in the short-range problem, which he regarded almost as a problem of extrapolation from the given initial condition. The process used, however, is not one of crude extrapolation using, say, only the observed rates-of-change of the elements. It is essentially dynamical, using simplified forms of the classical equations of motion of hydrodynamics. The Swedish meteorologist C.-G. Rossby had shown some years earlier that a characteristic feature of mid-tropospheric motion, the tendency of the upper winds to move in broad wave-like currents, could be explained by considering a simple inviscid barotropic fluid (i.e. without friction or horizontal gradients of temperature) moving adiabatically, if it is assumed that the vertical component of vorticity relative to axes fixed in space is conserved. The integration of the vorticity conservation equation, coupled with the assumption of the geostrophic balance between the motion and pressure fields, has now been shown to provide realistic predictions of the movements of the atmosphere at about the middle of the troposphere (about 5 or 6 kilometres above sea level) for periods of the order of 24 hours ahead when the initial situation is known in sufficient detail. The second stage envisaged by von Neumann was the production by mathematical reasoning of a mean pattern of motion closely resembling the general circulation. This also has been attacked with considerable success, but I shall have more to say of this later. We may thus state with confidence that significant progress has been made towards the solution of both the 'initial state' and the 'asymptotic state' problems. The 'intermediate state' problem is still unsolved, and it is with this problem that we are concerned in long-range forecasts.

The Forecasts of Weather-Lore

In the foregoing I have sketched the long-range forecasting problem as an exercise in mathematical physics. Mankind has, however, taken a different view throughout the ages, Inclement weather was long regarded as an indication of the displeasure of gods; good weather, equally, was a reward of virtue. In these circumstances it was natural that the myth of 'saint's day weather' should have arisen. This belief, which once was widespread, is that the weather of certain selected days indicates what will follow for long periods ahead. In this country the most popular of such beliefs is that related to St Swithin's Day (15th July), but I need hardly waste time in reciting the evidence for its untrustworthiness. St

Paul's Day (25th January), which was once held to provide an indication of the weather of the whole year, is another example; and there are many others. Quite apart from the records, which afford no support for such beliefs, it should be evident, from what I have said, that the influence of initial conditions cannot persist in the atmosphere for such long intervals.

Weather lore, the embodiment of folk-memories of past weather in proverbial sayings or rhymes, is completely untrustworthy for long-range forecasts. For forecasts covering a few hours only, many proverbial sayings (especially those emanating from the days of sail) are tolerably satisfactory; but there is no connection between, say, a plentiful crop of berries in the hedges in the autumn and the severity of the coming winter. We may also dismiss without further thought the long-cherished belief that the 'brute creation', as our forefathers called it, has some instinct denied to man that enables, for example cows and swallows to foresee long-term changes in weather.

From time to time, long-range forecasts of weather are published in our newspapers. These are the work of individuals outside the official services, and, occasionally, of commercial weather consultants. It is only rarely that the methods used are disclosed with anything like the detail customary in, say, a communication accepted by a learned society; and it is always difficult to judge the accuracy attained, for the language used is generally inprecise. Some measure of success is inevitable, for in a country like ours, which has a maritime climate and is situated in the main track of the Atlantic depressions, it is almost as difficult to be consistently wrong as to be consistently right in long-range forecasts! My impression is that most of these forecasts are like old-fashioned pharmaceutical mixtures—they are made up of a bit of everything, from superstition to scientific fact—and it is rare to find an amateur long-range forecaster who is able or willing to state in simple unequivocal language exactly how he composed his prediction.

Of one thing we may be quite certain—any method which claims to be able to produce reliable forecasts of the weather of any given day in a given locality months or even years ahead is not based upon accepted scientific principles. In this connection I cannot do better than to quote the words of the President of the American Meteorological Society regarding his Society's policy on professional ethics. In dealing with complaints about nonethical practices among meteorologists he writes of those:

> . . . . in which—to put it bluntly—real quackery is involved. This might be concerned, for example, with wildly extravagant claims of amazing accuracy in forecasting the day-to-day weather six months—or six years—in advance. Now every meteorologist nourishes the faint but unquenchable hope that one day this will be possible. But if that day does arrive, it will be marked—we would hope—not by a spectacular story in the Press or in a trade magazine but by a serious article in a reputable scientific journal, in which the scientific basis for the technique is exposed to the scrutiny and criticism of the scientific community with some reproducible statistics verifying the results. . . . Every meteorologist is familiar with the kind of long-range prediction that can be made by randomizing the climatological statistics on clear, cloudy and rainy days, and with a tolerance of one day, can provide results that are impressive to the uninitiated. . . *

With this word of warning I think I may leave this aspect of the matter and proceed to look at methods which, although not yet successful, are at least 'respectable ' in the scientific sense.

The Statistical Approach

It is natural, in view of the stability of climate and the variability of weather, to look for weather cycles or periodicities. The amount of energy spent by meteorologists in searching for regular recurrences in the distribution of pressure, temperature and rainfall, has been enormous, but the results have been of little use in the practical problem of foreseeing marked departures from the climatic averages. The weather-cycle question was, I think, finally settled by Sir David Brunt's painstaking periodgram analysis of the records of six widely separated European meteorological stations which had exceptionally long and reliable records. His work brought to light many constituent waves which satisfied the mathematical tests for reality, but in every case the amplitudes were too small to allow them to be used with confidence to predict, say, the nature of a coming winter in Europe. If weather cycles sufficiently stable and well-defined to be of use in practical long-range forecasting existed, they would certainly have been discovered and put to good use before now.

Earlier in this lecture I stated that the sun is the only significant source of energy for atmospheric motion, and it is appropriate, in speaking to illuminating engineers, that I should devote some attention to the possibility of variations in the solar energy output being related to major weather changes. This is a problem that has received considerable attention from meteorologists.

The sun is usually regarded by meteorologists as a black body with a surface temperature of the order of 6,000°K. Actually, this temperature applies chiefly

* Bull. Am. Met. Soc., 41, 659-660 (1960)

to the optically-measured spectrum of waves greater than $0{\cdot}45\mu$ in length. For shorter wave lengths, the 'black body' temperature of the sun is somewhat lower, but solar output contains waves of length varying from $0{\cdot}15\mu$ to 4μ. No radiation of wavelength shorter than $0{\cdot}29\mu$ is received at the earth's surface, because of absorption by ozone at great heights, and there is very little energy in the longest waves ($>3\mu$). By far the greater part of the observational work has been devoted to examination of the band between $0{\cdot}29\mu$ and $2{\cdot}5\mu$. The *solar constant* is defined as the mount of energy which, in one minute, reaches a square centimetre of plane surface placed perpendicularly to the sun's rays outside the atmosphere when the earth is at its mean distance from the sun. Its value is very nearly 2 cal cm^{-2} min^{-1}.

In the determination of the solar constant, use is made chiefly of data collected by mountain observatories, but even so, considerable extrapolation is called for and allowance has to be made for absorption by air and foreign matter in the atmosphere. Short-period changes in the solar constant, which must be small, are thus difficult to detect. Abbott has claimed to have found real variations related to large-scale weather changes, but his conclusions are not generally accepted. It seems undeniable that the energy emitted by the sun does fluctuate from time to time, but such variations are confined to small fractional changes, of the order of 1 or 2 per cent of the solar constant, and it is still debatable whether radiation measurements made in the lower atmosphere are sufficiently accurate to reveal such changes.

Telescopic studies show that the surface of the sun is very granular. The most easily observed features are sunspots (dark areas, roughly circular, usually in groups, with intense magnetic fields), faculae (bright areas), and flares, which are accompanied by emissions of hydrogen. Only sunspots have been observed long enough to allow their time-variations to be studied in detail. Sunspots are easily counted, and the record, which goes back about 200 years, shows that the number visible at any time exhibits an average period of about eleven years, with variations between seven and seventeen years. But even if the periodicity is not very regular we can speak with certainty of years of sunspot maxima and minima, and it is natural that many attempts have been made to relate changes in sunspot numbers to changes in weather.

The evidence, both for and against, a real relation is tantalizing. Perhaps the most famous parallelism is that between the level of Lake Victoria Nyanza (a measure of tropical rainfall) and sunspots between 1902 and 1921 as shown in Fig. 1. Here the correlation coefficient is 0·88. Yet the closeness of this agreement was not repeated in exhaustive world-wide investigations made by Sir Gilbert Walker, who dealt with rainfall, pressure and temperature in many regions. His results show conclusively that a simple correlation of annual means of sunspot numbers and weather elements cannot provide a reliable means of foretelling the nature of the coming seasons.

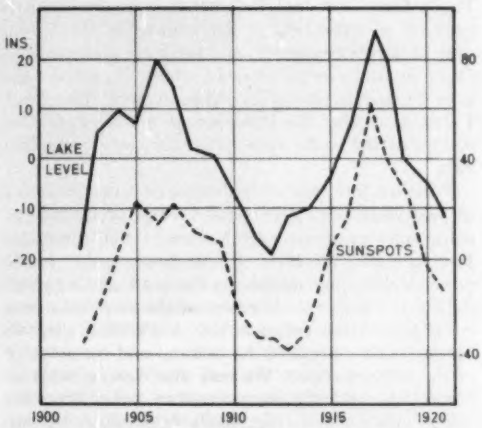

Fig. 1 Variations of water level in Victoria Nyanza from 1902-21 *and mean number of sunspots occuring in the same period. (From 'Manual of Meteorology' by Sir Napier Shaw. Cambridge University Press,* 1925.)

If, however, we consider secular variations in climate that is, cycles or changes of weather over large areas completed within a century—there does seem to be some evidence of the influence of the sunspot cycle, even if there is no strict correspondence. Some workers have found indications of an eleven-year cycle of temperature in the tropics, the lower temperatures occurring at the times of sunspot maxima, and it has also been claimed that storm tracks tend to shift towards the equator during the same periods. If we accept such phenomena as real, we are still faced with the difficulty of finding an adequate physical explanation. If there is a connection between sunspots and weather, it is certainly complex and must be indirect; but the problem still attracts attention, possibly because sunspot numbers are the only index of irregular solar activity for which really long reliable records exist.

There is also evidence for very short period changes. Sudden bursts of short-wave radiation which accompany eruptions on the sun's surface seem capable of heating the very high atmosphere in a relatively short time, of the order of hours. Such 'explosive warmings' may, in turn, affect the

zonal distribution of pressure because of an accompanying displacement of the atmosphere at great heights. Modern investigations, in fact, seem to place more emphasis on the solar flare than on the sunspot as a possible clue to major climatic anomalies; but as yet there are few definite results.

Measurements of radiation received at the earth's surface are still too few to satisfy meteorologists and I would like here to put in a plea for more, especially by those not concerned directly with meteorology but who are well placed to fill the gaps. The artificial satellite also promises to provide a means of measuring the solar output with certainty. From the study of existing low-level observations, we feel fairly confident that there is little or no variability in the energy content of solar radiation in the visible and infra-red parts of the spectrum. There is moderate variability in the near ultra-violet, but the greatest uncertainty lies in the far ultra-violet which affects the temperature of the ozone layer. But it is by no means clear how changes in temperature in the highly attenuated ozonosphere can affect conditions in the troposphere, the region of weather—this is part of the general uncertainty of meteorology. It would be foolish, however, to neglect any chance, no matter how slender, of relating cause and effect in the atmosphere, and this is one of the reasons why the Meteorological Office has created a separate unit for high-atmosphere research using all the facilities, such as rockets and satellites, at our command.

Although, as we have seen, there are no regular cycles in weather of any value for public forecasts, it is nevertheless true that not all varieties of weather are equally probable on certain days of the year. A patient search of the records for this country has revealed, for example, a distinct tendency for the days immediately after Christmas to be stormy and for mid-September to be fine. Fig. 2 illustrates the distribution of singularities, as they are called, for the British Isles, as given by the late C.E.P. Brooks in *The English Climate**.

Singularities are too ill-defined and too irregular in appearance to constitute a sound basis for long-range forecasting, but the fact that they exist shows that the incidence of 'good 'and 'bad' weather is not entirely random. The best-known, but by no means the most reliable, singularities are the celebrated Buchan cold and warm periods. These were deduced in the last century by Alexander Buchan from an examination of Scottish records. They have little or no validity for London.

For reasons of time, I must pass over in very brief review some of the scientific work which has gone on in this country and abroad. In the Meteorological Office we have given considerable attention to the use of temperature analogues. From the data collected over the years it is possible now to produce tolerably reliable charts showing the long-term average or climatic temperature of the air near the surface for most of the Northern Hemisphere. This information, used in conjunction with charts of the actual mean temperature, makes it possible to examine the distribution of temperature anomaly, that is, the difference between the temperature for any period and the climatic value. When such charts were first produced, using five day means, it immediately became clear that there are distinct patterns of temperature anomaly, some of which move slowly and last well over a month. They should therefore be evident also on monthly-mean charts. A typical distribution of temperature anomaly over a large part of the Northern Hemisphere is shown in Fig. 3.

For practical reasons, most of the work has been done with monthly-means. It has involved the construction of the mean anomaly chart for the current month, followed by a search through past charts to see if there was a year when a similar

* English Universities Press (1954).

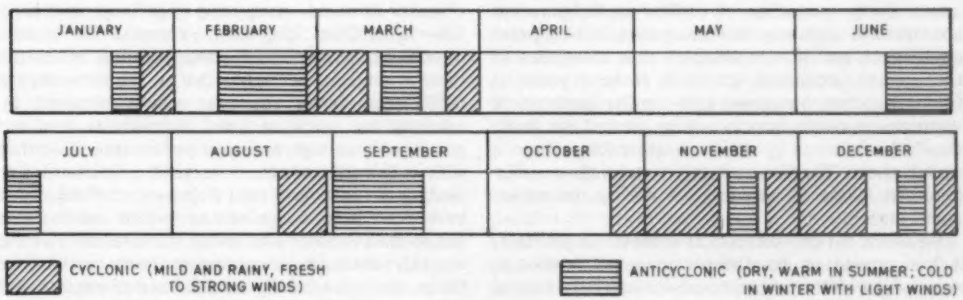

Fig. 2. The main singularities in British weather

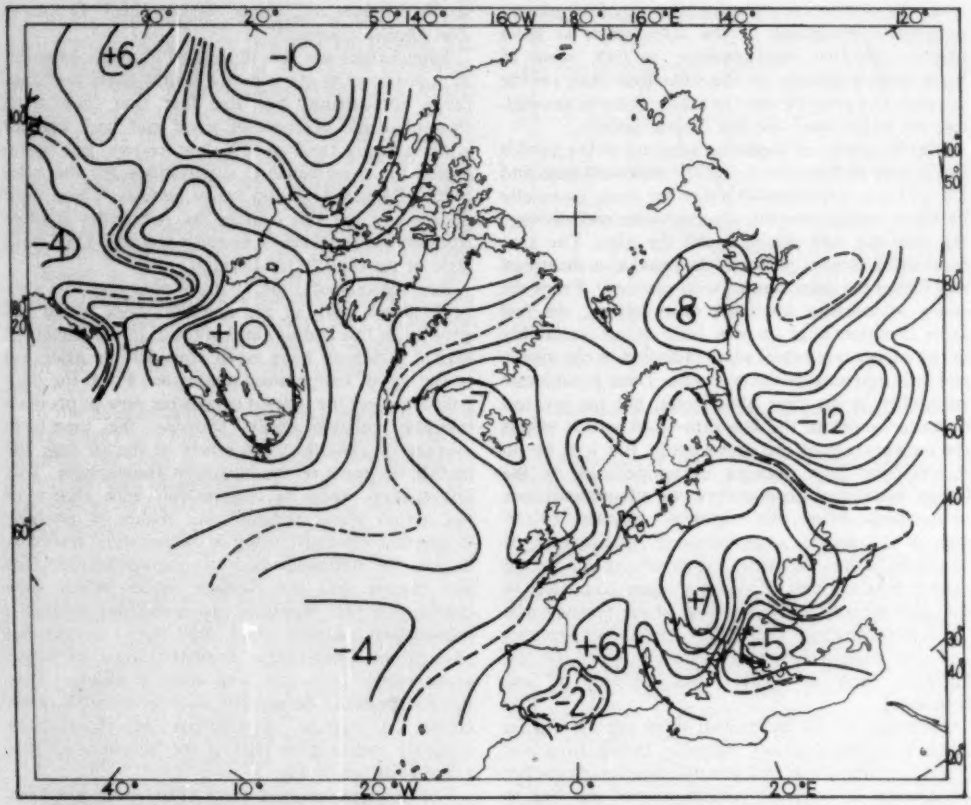

Fig. 3. A typical distribution of temperature anomaly over part of the Northern Hemisphere.

pattern existed during the same month. (This restriction was deemed necessary to ensure approximate correspondence of radiation income and expenditure.) The argument then runs as follows: if, as seems likely, anomalies of surface air temperature are linked in some way with anomalies in the general circulation, and if it is accepted that anomalies in the general circulation are likely to be a guide to future weather, occasions with similar patterns of temperature anomaly over a large part of the globe should be followed by similar weather for perhaps a month ahead. The 'forecast' then repeats the weather observed in the 'analogue year' during the subsequent month.

So much for the theoretical scheme. In practice, it has proved to be difficult to select 'analogue years', for with the limited number of charts available and the ability of the atmosphere to produce a seemingly endless variety of patterns, there is never exact correspondence and considerable judgment has to be used.

The forecasts produced by this method are limited to statements concerning the departure of the main climatic elements—temperature, pressure and rainfall—from their long-term averages. The results have been, on the whole, disappointing. Although there is evidence of 'skill'—that is, the forecasts are significantly better than the results obtained by selecting the 'analogue year' at random—they are not reliable enough for open publication. Together with a few remarkable successful predictions (including the extremely cold February of 1956), there have been many occasions on which the forecast would have misled. The research continues, but the monthly forecasts are circulated only within the Office, and then chiefly as a matter of interest and not as an official guide to answers to enquiries.

The national services which appear to devote

most attention to the problem of monthly forecasts are those of the USA, USSR, the Federal Republic of Germany and France. In detail, the processes used differ considerably, but basically they have a good deal in common. In the USA much use is made of charts based on five-day or longer averages of the pressure and motion fields over the whole of the Northern Hemisphere. On such charts the individual depressions and small anticyclones are smoothed out, leaving only certain large-scale features which have been called 'centres of action'. There are good grounds for believing that these features are real physical entities, and not simply a product of the smoothing process, for they tend to recur in certain areas and show continuity in successive charts. The monthly forecasts produced as a result of the study of the kinematics and thermodynamics of these large-scale features again show 'skill', but they are not as reliable as one could hope.

This method of analysis clearly leads to a study of the approach to the general circulation by averages over increasing periods. In the final section of this lecture I shall try to indicate the lines of attack which seem to me to be the most promising.

The Dynamic Approach

At this stage we may, I think, take heart by looking at the history of astronomy. Before Copernicus, Kepler and Newton, the apparent motions of the heavenly bodies were regarded as extremely complex, requiring a complicated geometrical model of curves derived from the circle for their description. The overthrow of the geocentric model by Copernicus, followed by Kepler's discovery of elliptic orbits and the kinematical laws of planetary motion, and finally, the enunciation of the devastatingly simple but all-powerful law of universal gravitation by Newton, reduced the main problems of spherical astronomy to matters of relatively simple calculation. Later, the telescopic discovery of Neptune from calculations of perturbations in the orbit of Uranus verified one of the most spectacular forecasts ever made by science.

Is there an analogy here for meteorology? The problems of spherical astronomy are simple compared with those of meteorology, but they suggest a useful way of looking at the matter. Earlier in this lecture I referred briefly to von Neumann's asymptotic problem, that of producing the pattern of the general circulation by purely mathematical reasoning from certain simple postulates. We know the magnitude and geometrical disposition relative to the earth of the primary source of the energy of the circulation, and we also know, at least approximately, the broad pattern of incoming and outgoing radiation on the earth. Further, if the earth and its atmosphere are imitated in the laboratory by a circular rotating vessel containing water heated at the rim and cooled at the centre, patterns resembling those observed in the general circulation develop. This suggested to the American meteorologist N. A. Philips that it might be possible to derive similar patterns by mathematics, by the use of reduced forms of the equations of fluid motion with the basic distribution of the heat sources represented by simple functions of latitude.

Despite these simplifications, the work requires the use of a large high-speed computer. With such a machine, an atmosphere at rest subject to the thermal stresses caused by the uneven distribution of radiation over the earth and subject also to the effects of the earth's diurnal rotation can be shown by integration of the equations of motion to develop initially a definite pattern of flow, which, however, bears only a slight resemblance to the actual circulation. An initial 'turbulent' flow pattern is then defined by the introduction of a small random disturbance. After a period corresponding to a real time-interval of between a week and a month a steady pattern forms which bears a tolerably close resemblance to the observed mean circulation. The major wind belts—the sub-tropical trades, the mid-latitude westerlies and the polar easterlies—are all reproduced. More recently, J. Smagorinsky, of the US Weather Bureau, has extended this work to produce (still with simple basic postulates) an even closer resemblance to the observed pattern of mean winds over the globe by numerical integration of the primitive equations of fluid motion.

These are striking achievements. They suggest that global meteorology may have reached the 'Kepler-Newton' stage, in that primary circulation can be accounted for (at least in broad terms) by the methods of mathematical physics, starting from extremely simple hypotheses. It seems that it can only be a matter of time before a satisfactory quantitative theory of the general circulation will be formulated. This suggests that ultimately it will be possible to calculate the main effects of specified perturbations of the circulations, a first step towards a 'cause-and-effect' sequence in, say, a long dry summer or a bitterly cold winter.

The mathematical studies to which I have referred above are true experiments. It is impossible to conduct physical experiments in the atmosphere on a scale comparable with the phenomena of weather, and laboratory experiments with fluids are, in the main, too unrealistic to be of use. The high-speed computer enables the meteorologist to fill the gap. In these investigations he is not trying to find a proof

of a theorem, but to ascertain the effect of certain trial hypotheses upon the final pattern.

The planet Neptune was discovered after Adams and Leverrier had indicated its orbit from a study of the perturbations of Uranus. Is it too much to hope that sometime in the future the arrival of a heat wave will be indicated in advance by the study of the perturbations of the general circulation? This is perhaps unqualified optimism, for so far it has proved impossible to isolate any single 'cause' of a climatic anomaly, but it is perhaps possible to hazard the prediction that only in this way will the long-range forecasting problem, the most intractable puzzle of meteorology, be solved.

Conclusion

The long-range forecasting problem is, in many ways, the most important problem of operational meteorology. Its solution would be of the utmost benefit to mankind, comparable with the establishment of the calendar or of reliable tide-tables. It is by no means certain that it can be solved, and it is something of an act of faith on the part of meteorologists to continue with the research in view of the record of failure so far. But the prize is so great, and the chase so exciting, that it is as certain as anything can be in science that we who study the restless ocean of air that surrounds the earth will not give up.

Vote of Thanks

MR W. T. SOUTER in proposing a vote of thanks to the lecturer said:

It is my very pleasant duty and privilege to propose a very sincere and warm vote of thanks to Sir Graham for presenting this sixth Trotter-Paterson Memorial Lecture this evening, and to record our appreciation of his most interesting address.

As our President said at the beginning, the Trotter-Paterson Memorial Lecture is a very important event in our sessional programme and we all look forward to it as being a worthy tribute to the two Past-Presidents whom this lecture commemorates, and who made such great contributions in the field of illumination and devoted so much time and effort in the interests of our Society.

We have been most fortunate and honoured by the sequence of distinguished scientists who have undertaken this Memorial Lecture since its inception, and tonight we are very much indebted to Sir Graham for the added lustre he has brought to these records.

The weather is a topical subject to all of us in these maritime islands with the capricious climate to which we are subjected and I imagine that ever since humans could communicate with one another the weather has been a popular conversational gambit.

While acknowledging the benefits long-term weather forecasting might bring to the welfare of the nation, members might perhaps be excused the selfish hope that Sir Graham might have given some hints which would help them to arrange their holidays during the period covering that fleeting experience which we call our English summer. Apart from the possible singularity occurring in early September it would seem that science today cannot give us any reliable method of forecasting that far. On the other hand, science has progressed to the extent of being able to disillusion us with regard to the fallibility of St Swithin and other weather-minded saints. While there is no established scientific basis of forecasting as yet we must hope that the progress in space travel, robot weather space ships, etc., will assist our scientists in their further investigation of this subject, and we wish you, sir, and your colleagues success in your further endeavours.

The subjects covered by the Memorial Lecture are not directly related to lighting, but it is natural that we endeavour to find some link; and I am reminded that Mr Waldram, who is to second my proposal, has carried out investigation covering the photometric properties of the upper atmosphere. I hope that he will say a few words in this connection and with this in view I will now make my official proposition, that the members of this Society accord a very sincere vote of thanks to Sir Graham for presenting this sixth Trotter-Paterson Memorial Lecture this evening, and record our appreciation of his most interesting address.

MR J. M. WALDRAM in seconding the vote of thanks said:

It is with very great pleasure that I find myself given the privilege of seconding the vote so ably proposed by Mr Souter for the lecture we have just heard.

I am sure none of us can have listened to Sir Graham without being amazed at the toughness of the meteorologist; he will not be put off by the elusiveness and capriciousness of the weather, but persists in his determination to unravel its mysteries. I think sometimes we are too easily put off by a problem when we see its complexity; we should take courage from the way in which they have, for example, abandoned the classical statistical approach, and found more success in other methods. In our much smaller field there have been cases where we have done that fairly recently. In studying the effects of street lighting on traffic accidents, for example, we found the usually formidable tool of statistics was too blunt, and we have got nearer to a solution by

re-stating the problems and using another approach.

Someone to whom I gave an invitation to tonight's lecture remarked, 'What on earth has that do to with lighting?' Indeed at first sight there is no obvious connection; but the charm of lighting is the variety of its contacts, and meteorology is a very important one.

It was during the war that we really found our two disciplines were coming together. Whenever you have to see or send light over any considerable distance it is the meteorological conditions which define the problem. We found that there were no data and we had to get them. I remember, Mr President, that on the committee set up by Mr Good you were working on zenith transmission, and after some observations on the brightness of stars you were able to cast some doubt on the astonomers' stellar magnitudes. So an illuminating engineer working on a meteorological problem managed to upset the universe, which is no mean feat.

Some of us were concerned with going up in aircraft and balloons to measure the photometric properties of the atmosphere, measuring its polar scatter and absorption at heights up to 10 km; and a joint meeting was held with the Royal Meteorological Society to discuss the results. This work is still going on, for I have just received a report dated September 1960 on new work in Australia using refined versions of the nephelometer we used and also of the Brewer-Beuttell integrating nephelometer. That little-known instrument was one of the most elegant pieces of apparatus I have ever met. The late Mr J. Beuttell, a meteorologist of great promise, was one of the designers; his name is held in affection in this Society, for his father is our oldest surviving Past President. So you see there are many links between us.

But there are also links with both the men whom this lecture commemorates. Some of the work to which I have referred was done in the laboratories which Sir Clifford Paterson led. It happened also that Mr Trotter heard that I had been up in captive balloons, and he sent me an account (not merely written but printed and bound by himself), describing his own experiences in the First World War—Trotter always beat us by a generation—when he went up in a *free* balloon to observe the blackout imposed to hamper the Zeppelin raids. He describes how his balloon 'bounced' on a cloud, and gave the meteorological explanation.

This lecture has not only fascinated us in the story it has told; it has close links with the Society and with the two men whom it is the purpose of the lecture to commemorate. We are grateful to those who chose so interesting a subject, from which we have much to learn, and we have been most fortunate in the choice of lecturer.

It is with great pleasure that I second the vote of thanks.

UDC 535.2 : 628.93

Nomenclature and Symbols Associated with Radiation Transfer Calculations

Summary

This Report proposes nomenclature and symbols which it recommends should be generally adopted when identifying certain concepts used in radiation transfer calculations. In making the proposals, consideration has been given to the terminology and symbols used in radiant heat transfer problems, as well as to those already used by workers concerned with interreflected light calculations.

The Report was prepared for the Fundamental Principles of Lighting Sub-Committee of the National Illumination Committee of Great Britain, by a panel comprising H. E. Bellchambers, P. Petherbridge and R. O. Phillips.

(1) Introduction

In recent years increasing attention has been given to methods for determining the radiant flux received on one surface from another of extended area. The need for such methods arises in problems of radiant heat transfer and of interreflections in lighting. Unfortunately, various workers in this general field have adopted different terminology and notations for certain basically similar concepts arising in the solution of these problems. The purpose of this Report is therefore:

(a) to list existing terms and symbols for the concepts, so emphasising the desirability for some agreement,
(b) to propose for general acceptance
  (i) a precise definition
  (ii) a suitable term
  (iii) a symbol
  for each of the concepts,
(c) to explain the reasons for the choice of terms and symbols.

The concepts have been defined in such a way as to make them independent of the type of radiant flux (visible or thermal) under consideration; however, since this Report is primarily intended for the lighting profession, a photometric interpretation of the concepts has been included.

The Report is not directly concerned with the interreflection of radiation between one surface and another but merely with a single transfer, usually of the primary flux alone or of the total flux from the emitting surface resulting on completion of the interreflection process.

Throughout the Report it is assumed that the radiating surfaces are uniformly diffusing and of uniform radiance or luminance and that every part of one surface can 'see' every part of the other surface.

(2) Basic Terminology

The following basic terms are used in order to ensure independence of the type of radiant flux. Reference should be made to the CIE International Lighting Vocabulary (1957) for precise definitions, and particularly for a distinction between the radiometric and photometric equivalents of each of the terms.

FLUX Radiant power emitted, transferred or received.

EMITTANCE (*at a point of a surface*)* The quotient of the flux emitted by an infinitesimal element of surface containing the point under consideration, by the area of that element.

FLUX DENSITY (*at a point of a surface*). The quotient of the flux incident on an infinitesimal element of surface containing the point under consideration, by the area of that element. (Flux Density corresponds to the irradiance or illumination at a point on the receiving surface.)

(3) Present Radiation Transfer Terminology and Symbols

The three radiant transfer concepts considered in this Report stem from the basic function expressing the flux density at a point on a surface due to an infinitesimal element of another uniformly diffusing surface of unit emittance (See Appendix). The first concept (the Configuration Factor—Proposal 2†)

* For visible radiation, the awkward π term appears in the flux transfer equations if the luminances of uniformly diffusely emitting surfaces are expressed in candelas per unit area. This can be avoided by using instead the luminous emittances (lumens per unit area) of these surfaces. The π term can also be avoided by expressing the luminances in foot-lamberts (or apostilbs), since there is a convenient 1 : 1 numerical relationship between the luminance in these units and the luminous emittance in lumens per sq. ft. (or lumens per sq. m.) of a uniform diffuser.

† The Proposals are given in Section 4.

is given by the integration of the flux over the whole of the emitting surface, the second concept (the Exchange Coefficient—Proposal 3) is given by a further integration over the whole of the receiving surface, and the third concept (the Form Factor—Proposal 4) is given by dividing this double integral by the area of the receiving surface.

If the flux transfer between two uniformly diffusing surfaces denoted by 1 and 2 is considered (Figs. 1, 2 and 3), several relationships appear to be in common use.

(3.1) Flux transfer between an infinitesimal element dS_1 of surface 1 and the whole of surface 2

This may be considered in two forms, viz.

$$\frac{\text{Flux density of } dS_1}{\text{Emittance of surface 2}}$$

$$\text{or} \frac{\text{Flux received on surface 2}}{\text{Flux emitted by } dS_1}$$

For visible radiation, the first quotient is equivalent to the illumination on dS_1 due to surface 2 of unit emittance (or unit luminance, in foot-lamberts or apostilbs).

At least the following terms and symbols have been used for this or similar concepts:

Angle Factor	$F(d1)_2$	M. Jakob reference 1
Configuration Factor	ϕ	J. H. McGuire reference 2
Illumination Factor		J. M. Waldram reference 3
Point Configuration Factor	$F_{dS_1\text{-}S_2}$	D. C. Hamilton and W. R. Morgan reference 4
Sky Factor (Facteur de Ciel)		CIE Vocabulary reference 5

(3.2) Flux transfer between the whole of surfaces 1 and 2

This may be considered in three forms.

(*3.2.1*) $$\frac{\text{Flux received on surface 1}}{\text{Emittance of surface 2}}$$

The following terms and symbols appear to have been used:

Exchange Factor	$e_{1,2}$	R. O. Phillips and S. J. Prokhovnik reference 6
Fonction d'Echange	E_{12}	R. Cadiergues reference 7
	N_2^1	J. Dourgnon reference 8
Geometric Flux	G_{12}	D. C. Hamilton and W. R. Morgan reference 4
Integrated Configuration Factor		J. H. McGuire reference 2
Wechselfunktion	$\Phi_{1,2}$	F. Squassi reference 9

(*3.2.2*) $$\frac{\text{Average flux density on surface 1}}{\text{Emittance of surface 2}}$$

$$\text{or} \frac{\text{Flux received on surface 2}}{\text{Flux emitted by surface 1}}$$

For visible radiation, the first quotient is equivalent to the average illumination on surface 1 due to surface 2 of unit emittance (or unit luminance, in foot-lamberts or apostilbs). The average illumination (in lm/ft^2 or lux) on a surface is considered to be given by the total luminous flux (in lumens) received on that surface, divided by the area of the surface (in sq. ft. or sq. m.).

At least the following terms and symbols have been used:

Angle Factor	F_{12}	M. Jakob reference 1
Configuration Factor	$F_{1\text{-}2}$	D. C. Hamilton and W. R. Morgan reference 4
		M. Jakob and G. A. Hawkins reference 10
Facteur de Forme	F_{12}	R. Cadiergues reference 7
	q_2^1	J. Dourgnon reference 8
Form Factor	f_{12}	R. O. Phillips and S. J. Prokhovnik reference 6
Geometrical Factor		ASHRAE Guide reference 11
I-Factor	I_{12}	J. A. Lynes reference 12
Illumination Factor		R. O. Phillips reference 13
Shape Modulus	$F_{1\to2}$	P. F. O'Brien reference 14
Winkelverhältnis	$\phi_{1,2}$	F. Squassi reference 9

(4) Proposals

In view of the current confusion, illustrated by the numerous and diverse terms and symbols listed in

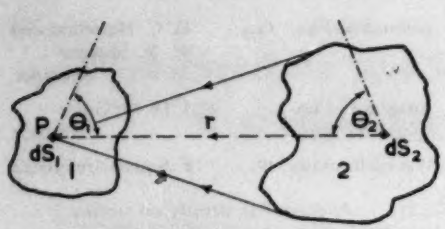

Fig. 1

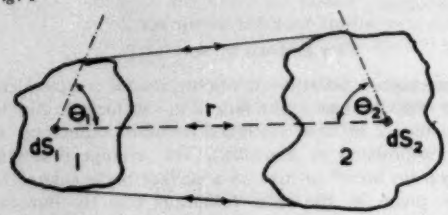

Fig. 2

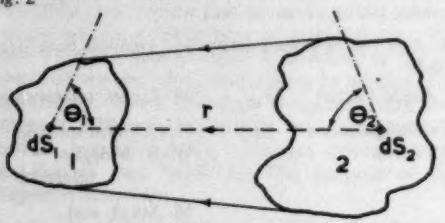

Fig. 3

the previous Section, some standardisation of terminology and symbols would appear desirable. The following Proposals are therefore made:

Proposal 1

That the radiation transfer concepts considered in the present Report should be independent of the type of radiation (visible or thermal) under consideration.

Proposal 2

In the case of radiation transfer between an infinitesimal surface element and a finite surface identified by the subscripts 1 and 2 respectively, as in Fig. 1, the concept defined by

$$\int_{S_2} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} \, dS_2$$

should be known as the *CONFIGURATION FACTOR* and have the symbol c_{12}

Proposal 3

In the case of radiation transfer between one finite surface and another identified by the subscripts 1 and 2 respectively, as in Fig. 2, the concept defined by

$$\int_{S_2}\int_{S_1} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dS_1 \, dS_2$$

should be known as the *EXCHANGE COEFFICIENT* and have the symbol $e_{1.2}$ or $e_{2.1}$

Note: This double integral equals

$$\int_{S_1} c_{12} \, dS_1 \text{ or } \int_{S_2} c_{21} \, dS_2$$

Proposal 4

In the case of radiation transfer between one finite surface and another identified by the subscripts 1 and 2 respectively, as in Fig. 3, the concept defined by

$$\frac{1}{S_1}\int_{S_2}\int_{S_1} \frac{\cos\theta_1 \cos\theta_2}{\pi r^2} dS_1 \, dS_2$$

should be known as the *FORM FACTOR* and have the symbol f_{12}

Note: This double integral equals $\frac{e_{1.2}}{S_1}$ or $\frac{e_{2.1}}{S_1}$

Proposal 5

That the preferred function for expressing by means of graphs, tables, etc., the transfer of flux between two finite surfaces should be independent of the direction in which the transfer occurs (the Exchange Coefficient).

Proposal 6

That the two surfaces between which the radiation is being transferred should be identified by an appropriate double subscript to the symbol. These two subscripts can be either numbers (e.g. c_{12}) or letters (e.g. f_{cw}).

Proposal 7

That in the case of Configuration Factor, which is a non-reversible quantity, the order of the subscripts should be determined by relating the first subscript to the infinitestimal surface element and the second subscript to the finite surface—see Proposal 2.

Proposal 8

That in the case of Form Factor, which is also a non-reversible quantity, the order of the subscripts should be determined by relating the first subscript to the surface whose area is the divisor of the double integral in the numerical expression defining Form Factor—see Proposal 4.

Proposal 9

That in the case of Exchange Coefficient, which is a reversible quantity, and where therefore the order of the subscripts is immaterial, the subscripts should be separated by a full stop to distinguish the corresponding symbol from those relating to non-reversible quantities.

(5) Significance of the Proposals

The significance of the Proposals put forward in the previous Section is outlined below, particular attention being given to the equivalents of the three concepts in terms of visible radiation; the development of the Proposals is dealt with in an Appendix.

(5.1) Configuration Factor

The Configuration Factor is a dimensionless quotient, but is non-reversible, so that the order of the subscripts is significant.

As defined in Proposal 2 the Configuration Factor can be regarded as equivalent to the flux density (irradiance or illumination) at the point P on surface 1 due to a uniformly diffusing surface 2 of unit emittance.

More generally, the Configuration Factor can be expressed by the following quotient:

$$c_{12} = \frac{\text{Flux density at point } r' \text{ on surface 1 due to surface 2}}{\text{Emittance of uniformly diffusing surface 2}}$$

The Configuration Factor can also be expressed (see second Section of Appendix) by the following ratio between two fluxes (radiant or luminous):

$$c_{12} = \frac{\text{Flux received on surface 2 from infinitesimal element } dS_1}{\text{Flux emitted by infinitesimal element } dS_1}$$

The concept of Configuration Factor is identical with that of the expression Sky Factor (Facteur de Ciel) used in natural lighting.

(5.2) Exchange Coefficient

The Exchange Coefficient is a reversible quantity having the dimensions of an area. Since the expression defining the Coefficient is symmetrical, the order of the subscripts to the symbol is immaterial, viz.

$$e_{1.2} = e_{2.1}$$

Exchange Coefficients have the important property of being directly additive; for example, the Exchange Coefficient of a surface 1 in relation to a complex surface comprising individual elements 2, 3, 4 . . . is given by $e_{1.2}+e_{1.3}+e_{1.4}+\ldots$ Exchange Coefficients also lend themselves more readily than Form Factors to tabular and graphical presentation (see Appendix).

As defined in Proposal 3, the Exchange Coefficient can be regarded as equivalent to the total radiant or luminous flux received on one of the surfaces (either 1 or 2) from the other uniformly diffusing surface of unit emittance.

More generally, the Exchange Coefficient can be expressed by the following quotient:

$$e_{1.2} = e_{2.1} = \frac{\text{Total flux on surface 1 (or 2) due to surface 2 (or 1)}}{\text{Emittance of uniformly diffusing surface 2 (or 1)}}$$

(5.3) Form Factor

The Form Factor is a dimensionless quotient, but is non-reversible, so that the order of the subscripts is significant.

As defined in Proposal 4, the Form Factor can be regarded as equivalent to the average flux density (average irradiance or illumination) on surface 1 due to a uniformly diffusing surface 2 of unit emittance.

More generally, the Form Factor can be expressed by the following quotient:

$$f_{12} = \frac{\text{Average flux density on surface 1 due to surface 2}}{\text{Emittance of uniformly diffusing surface 2}}$$

The Form Factor can also be expressed (see second Section of Appendix) by the following ratio between two fluxes (radiant or luminous):

$$f_{12} = \frac{\text{Flux received on surface 2 from surface 1}}{\text{Flux emitted by surface 1}}$$

The Form Factor and Exchange Coefficient are related by:

$$S_1 f_{12} = e_{1.2} = c_{2.1} = S_2 f_{21}$$

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Appendix

Development of the Proposals

Definitions of the three concepts

It will be seen from Proposals 2, 3 and 4 that the three concepts have been defined geometrically, rather than radiometrically or photometrically. In the case of Figs. 1 and 3, flux (radiant or luminous) is assumed to be transferred from an infinitesimal element of area dS_2 on surface 2 to an infinitesimal element of area dS_1 at point P on surface 1; in the case of Fig. 2, the direction of the flux transfer is immaterial.

The two infinitesimal elements are assumed to be at a distance r apart, and the perpendiculars to their surfaces are assumed to be inclined at angles θ_2 and θ_1 respectively to the line joining the two elements.

The flux density at point P on surface 1 due to the uniformly diffusing infinitesimal element dS_2 of unit emittance is given by:

$$\frac{1}{\pi} \cdot \frac{\cos\theta_1 \cos\theta_2}{r^2} \cdot dS_2$$

(An explanation for the presence of the π term is given in a footnote to Section 2 of the Report.)

The flux density at point P on surface 1 due to uniformly diffusing surface 2 of unit emittance (the Configuration Factor) is given by the integration of this function over the whole of surface 2 as in Proposal 2.

The total flux on surface 1 due to uniformly diffusing surface 2 of unit emittance (the Exchange Coefficient) is then given by the integral of the Configuration Factor over the whole of surface 1 as in Proposal 3.

The average flux density on surface 1 due to uniformly diffusing surface 2 of unit emittance (the Form Factor) is then given by the quotient of the Exchange Coefficient and the area of surface 1 as in Proposal 4.

Derivation of alternative forms of concepts

Configuration Factor

First consider the radiation transfer between an infinitesimal element dS_1 and a finite surface 2.

Let M_1 and M_2 be the emittances (fluxes *emitted* per unit area) of the element and surface respectively,

dF_1 and F_2 be the fluxes *received* by the element and surface respectively,

dS_1 and S_2 be the areas of the element and surface respectively.

In Section 5 of the Report it was pointed out that the Exchange Coefficient could be expressed by the following quotient:

$$e_{1.2} = e_{2.1} = \frac{\text{Total flux on surface 1 (or 2) due to surface 2 (or 1)}}{\text{Emittance of uniformly diffusing surface 2 (or 1)}}$$

Therefore, if surface 2 is considered to be the source, then $e_{2.1} = \frac{dF_1}{M_2}$; whereas if element dS_1 is considered to be the source, then $e_{1.2} = \frac{F_2}{M_1}$.

But $e_{2.1} = e_{1.2}$. Dividing through by dS_1 gives:

$$\frac{e_{2.1}}{dS_1} = \frac{e_{1.2}}{dS_1} = \frac{dF_1}{dS_1 \times M_2} = \frac{F_2}{dS_1 \times M_1}$$

$$\text{or} \quad \frac{\text{Flux density on } dS_1}{\text{Emittance of 2}} = \frac{\text{Flux received on 2}}{\text{Flux emitted by } dS_1}.$$

But in Section 5 of the Report it was pointed out that the first of the above quotients was equal to c_{12}.

$$\text{Hence } c_{12} = \frac{\text{Flux received on 2}}{\text{Flux emitted by } dS_1}$$

or Configuration Factor can also be expressed by the ratio between two fluxes.

It should be noted that for the same numerical value of Configuration Factor, the direction of the radiation transfer is different depending on whether the Factor is expressed as the quotient of flux density and emittance (surface 2 the source in the above derivation) or as the ratio between two fluxes (element dS_1 the source in the above derivation).

Form Factor

Now consider the radiation transfer between two finite surfaces 1 and 2.

Let M_1 and M_2 be the emittances of surfaces 1 and 2 respectively,

F_1 and F_2 be the fluxes received by surfaces 1 and 2 respectively,

S_1 and S_2 be the areas of surfaces 1 and 2 respectively.

If surface 2 is considered to be the source, then $e_{2.1} = \frac{F_1}{M_2}$; whereas if surface 1 is considered to

be the source, then $e_{1.2}=\frac{F_2}{M_1}$. Equating and dividing through by S_1 gives:

$$\frac{e_{2.1}}{S_1}=\frac{e_{1.2}}{S_1}=\frac{F_1}{S_1\times M_2}=\frac{F_2}{S_1\times M_1}$$

$$\text{or}\quad \frac{\text{Average flux density on 1}}{\text{Emittance of 2}}=\frac{\text{Flux received on 2}}{\text{Flux emitted by 1}}$$

But in Section 5 of the Report it was pointed out that the first of the above quotients was equal to f_{12}.

$$\text{Hence } f_{12}=\frac{\text{Flux received on 2}}{\text{Flux emitted by 1}}$$

or Form Factor can also be expressed by the ratio between two fluxes.

It should be noted that for the same numerical value of Form Factor, the direction of the radiation transfer is different depending on whether the Factor is expressed as the quotient of average flux density and emittance (surface 2 the source in the above derivation) or as the ratio between two fluxes (surface 1 the source in the above derivation).

Terminology

Consideration was given to whether each of the three radiation transfer concepts should be called a 'Coefficient', 'Function', 'Factor' or 'Modulus'. It was felt that 'Factor' more appropriately identified each concept as one of two quantities which, when multiplied together, produced a given product; for example:

$c_{12}\times$emittance of surface 2=flux density on dS_1.

In CIE nomenclature, however, the term 'Factor' specifically refers to a dimensionless multiplier. The second concept, which has the dimensions of an area, has therefore been identified as a 'Coefficient'.

Section 3 of the Report demonstrates the wide range of terms which have been used to identify the individual radiation transfer concepts. Considerations determining the choice of terms recommended in this Report are given below.

Surface/point radiation transfer

Both Hamilton & Morgan and McGuire use variants of the single term 'Configuration Factor' for both the surface/point and surface/surface radiation transfer concepts. It was felt, however, that a gain in clarity and precision would be achieved by using entirely different terms to identify these two concepts.

'Configuration Factor', used alone, was therefore adopted to identify the surface/point radiation concept; 'Sky Factor', which is well established in daylighting terminology, identifies this transfer in natural lighting calculations.

Surface/surface radiation transfer

The radiation transfer concept dealt with in Proposal 3 is, in fact, the integration of the Configuration Factor over the whole of surface 1 (as in the first Section above). McGuire's 'Integrated Configuration Factor' is therefore appropriately named. On the other hand, as mentioned above, it was felt that a gain in clarity and precision would be achieved by using entirely different terms to identify Configuration Factor and its integral.

'Transfer Coefficient' was considered on the basis that the concept is concerned with the single transfer of flux, either from surface 2 to surface 1 or from surface 1 to surface 2. All three concepts are, however, concerned with the transfer of flux from one surface to another, and not merely the concept of Proposal 3.

'Exchange Coefficient' has the merit that it suggests the interchangeable nature of the concept ($e_{1.2}=e_{2.1}$), an attribute which often simplifies determining the magnitude of the Coefficient by enabling the roles of the emitting and receiving surfaces to be exchanged; moreover the term is in close agreement with the corresponding French and German terms, Fonction d' Echange and Wechselfunktion respectively. These considerations outweigh the objection that 'Exchange Coefficient' would appear to refer specifically to the double transfer (inter-change) of flux between surfaces 1 and 2.

Similar considerations of international conformity on terminology led to the adoption of the term used to identify the radiation transfer concept dealt with in Proposal 4; 'Form Factor' conforms with the French term 'Facteur de Forme' and with the American use of the symbol F.

No confusion is expected with the term 'form factor' used in electrical engineering.

Symbols

Section 3 of the Report also demonstrates the wide range of symbols which have been used to identify the individual radiation transfer concepts.

It was decided that for ease of remembrance, the symbol should in each case be the initial letter of the corresponding term; a lower case letter was chosen, since it was felt to be more appropriate to a factor or coefficient. An additional reason was that the capital letter F is already used in standard vocabularies as the symbol for luminous flux.

No confusion is expected with exponential e, or with symbols such as f_3^1 which may be used in utilised flux calculations.

Position of subscripts

The position of the subscripts advocated by Dourgnon (reference 8) was considered as an

alternative to that given in Proposal 6. It was felt, however, that a possible disadvantage of Dourgnon's convention would be that, for example, N_3^2 could be mistaken for N_3 squared.

Determination of order of subscripts

The use of subscripts to the symbols *c*, *e* and *f* to indicate not only the surfaces between which the radiation is being transferred, but also the direction in which the transfer is being made, has considerable merit.

The direction of the transfer could be simply indicated by an arrow between the subscripts, but this has the objection that the complete symbol cannot be typed.

An alternative solution would appear to be to determine the direction of the radiation transfer from the order in which the subscripts are written. For the same numerical value of Configuration Factor or Form Factor, however, the direction of the transfer is different depending on whether the Factor is expressed as the quotient of flux density and emittance or as the ratio between two fluxes. (See the second Section above.)

To overcome this difficulty, Proposals 7 and 8 have been put forward, in which the orders of the subscripts are independent of the direction of the radiation transfer, but are dependent instead on an arbitrary convention based on the geometrical definitions of Configuration Factor and Form Factor. The convention results in the first subscript of the symbols for Configuration Factor and Form Factor referring to the emitting surface when these two Factors are considered as the ratios of two fluxes, and to the receiving surface when these two Factors are considered as the quotient of flux density and emittance. Confusion does not usually arise in the latter case, since those workers who prefer to think in terms of illumination and emittance (or luminance) usually regard c_{12} or f_{12} as the illumination *received* on one surface from another, and thus know that the first subscript (1) refers to the receiving surface.

The convention conforms with current usage in this country, and with the order used by such other workers as Dourgnon (reference 8), Hamilton & Morgan (reference 4), Jakob (reference 1), O'Brien (reference 14) and Phillips & Prokhovnik (reference 6). The convention is also convenient when matrix techniques are applied to interreflection problems, since the order of the subscripts then agrees with the usual matrix notation.

Presentation of radiation transfer data

In radiation transfer calculations it is often necessary to know the numerical values of the Exchange Coefficient and Form Factor for various sizes and shapes of surfaces orientated in different directions with respect to one another, the information being made available in either graphical or tabular form.

In Section 5 of the Report it was pointed out that Exchange Coefficient is a reversible quantity having the dimensions of an area, whereas Form Factor is a non-reversible quantity which is dimensionless. There is some feeling, e.g. Dourgnon (reference 8), that the quantity whose numerical value is made available in one or other of the forms indicated above should be dimensionless. On the other hand, the two Form Factors related to a pair of surfaces can be obtained from the single Exchange Coefficient related to that pair of surfaces by dividing by the areas of the individual (receiving) surfaces. The presentation of Exchange Coefficients, rather than Form Factors, in graphical or tabular form therefore leads to a considerable reduction in the amount of data required for radiation transfer calculations. This is considered to outweigh any objections to Exchange Coefficient based on its dimensional character, and leads to Proposal 5.

When the radiation transfer is between two adjacent rectangular surfaces having a common side, such as a wall of length L and height H and a ceiling of length L and width W, the presentation of the data in tabular or graphical form can be still further reduced if the room height and width are expressed as ratios of the length of the common side, viz. $\frac{H}{L}$ and $\frac{W}{L}$. The values then given would in fact be of (Exchange Coefficient)/L^2 which is a dimensionless quantity, and the Exchange Coefficients themselves could be obtained by multiplying the values by L^2. In most cases, however, it is the Form Factors which are required; these can be determined from the tabular or graphical values by dividing by $\frac{H}{L}$ or $\frac{W}{L}$ for the wall and ceiling respectively.

Additions to the List of Members

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The Council has accepted the following applications for Fellowship of the Society:

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H. M. Ferguson
G. K. Lambert
J. Longmore

Diploma Membership

The Council has accepted applications for the Society's Diploma in Lighting Engineering from the following, who are now Diploma Members:

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E. G. Maddock
P. D. Parker
M. Wood-Robinson

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Printed in England by
The Shenval Press Ltd, London, Hertford and Harlow
and published by
THE ILLUMINATING ENGINEERING SOCIETY
32 Victoria Street, London, SW1

Annual Subscription to Non-Members — £2 . 2 . 0
Price per number to Non-Members — 10s 6d